Enabling Technologies

Enabling Technologies: Innovation Landscape

- Utility-scale Batteries
- Behind-the-meter batteries
- Electric-vehicle smart charging
- Internet of Things
- Artificial Intelligence and Big Data
- Blockchain

International Renewable Energy Agency

UTILITY-SCALE BATTERIES

INNOVATION LANDSCAPE BRIEF

IRENA
International Renewable Energy Agency

ISBN 978-92-9260-139-3

Citation: IRENA (2019), *Innovation landscape brief: Utility-scale batteries*, International Renewable Energy Agency, Abu Dhabi.

ACKNOWLEDGEMENTS

This report was prepared by the Innovation team at IRENA's Innovation and Technology Centre (IITC) with text authored by Arina Anisie and Francisco Boshell, with additional contributions and support from Santosh Kamath, Harsh Kanani and Shikhin Mehrotra (KPMG India).

Valuable external review was provided by Patrick Clerens and Jean-Michel Durand (EASE Storage Association), Derek Stenclik and Vlad Duboviks (General Electric), and Michael Taylor, Pablo Ralon, Martina Lyons, Nina Litman-Roventa and Paul Komor (IRENA).

Report available online: www.irena.org/publications
For questions or to provide feedback: publications@irena.org

DISCLAIMER

www.irena.org

IRENA
International Renewable Energy Agency

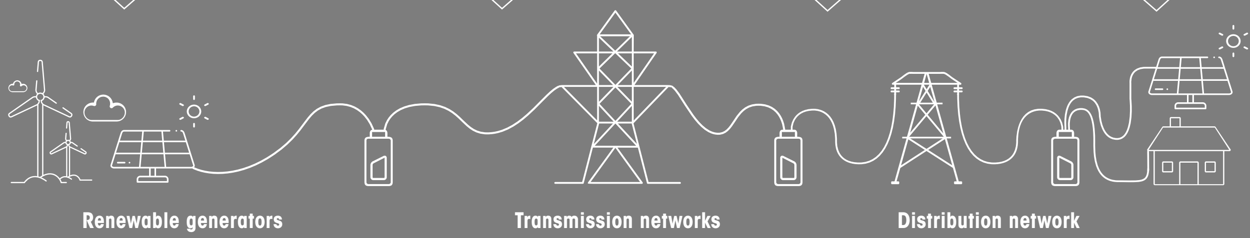
1 BENEFITS

Batteries can provide services for system operation and for solar PV and wind generators, defer investments in peak generation and grid reinforcements.

RENEWABLE GENERATORS
- Reduced renewable curtailment
- Renewable capacity firming

SYSTEM OPERATION
- Frequency regulation
- Flexible ramping
- Black start services

INVESTMENT DEFERRAL
- Transmission and distribution congestion relief
- Energy shifting and capacity investment deferral



2 KEY ENABLING FACTORS

- Reduced upfront costs
- Conducive regulatory framework
- Pilot projects and knowledge dissemination

3 SNAPSHOT

- 10 GW of battery storage is deployed globally (2017)
- Batteries with a total annual production of 27 MWh are providing ¼ of total enhanced frequency regulation capacity in UK.
- A demonstration project in US showed that a 4 MW/40 MWh battery can save USD 2 million in fuel costs and 400 hours of grid congestion.

WHAT ARE UTILITY-SCALE BATTERIES?

Stationary batteries can be connected to distribution/transmission networks or power-generation assets. Utility-scale storage capacity ranges from several megawatt-hours to hundreds. Lithium-ion batteries are the most prevalent and mature type.

UTILITY-SCALE BATTERIES

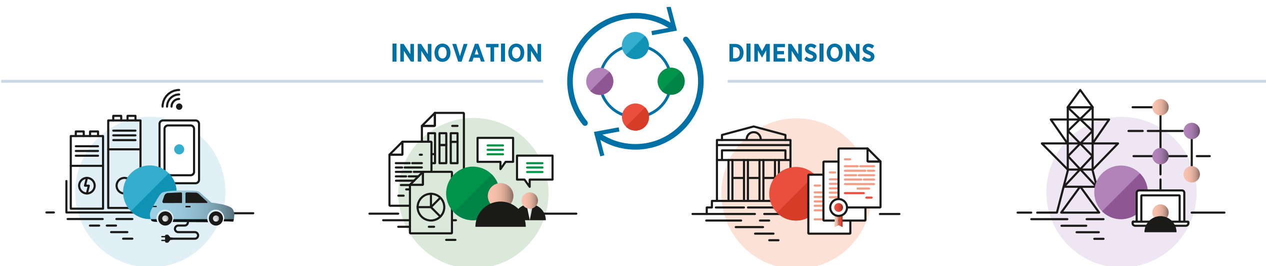
Battery storage **increases flexibility** in power systems, enabling optimal use of variable electricity sources like solar photovoltaic (PV) and wind energy.

ABOUT THIS BRIEF

This brief is part of the IRENA project "Innovation landscape for a renewable-powered future", which maps the relevant innovations, identifies the synergies and formulates solutions for integrating high shares of variable renewable energy (VRE) into power systems.

The synthesis report, *Innovation landscape for a renewable-powered future: Solutions to integrate variable renewables* (IRENA, 2019), illustrates the need for synergies among different innovations to create actual solutions. Solutions to drive the uptake of solar and wind power span four broad dimensions of innovation: enabling technologies, business models, market design and system operation.

Along with the synthesis report, the project includes a series of briefs, each covering one of 30 key innovations identified across those four dimensions. The 30 innovations are listed in the figure below.



ENABLING TECHNOLOGIES

1 Utility scale batteries
2 Behind-the-meter batteries

3 Electric-vehicle smart charging
4 Renewable power-to-heat
5 Renewable power-to-hydrogen

6 Internet of Things
7 Artificial intelligence and big data
8 Blockchain

9 Renewable mini-grids
10 Supergrids

11 Flexibility in conventional power plants

BUSINESS MODELS

12 Aggregators
13 Peer-to-peer electricity trading
14 Energy-as-a-service

15 Community-ownership models
16 Pay-as-you-go models

MARKET DESIGN

17 Increasing time granularity in electricity markets
18 Increasing space granularity in electricity markets
19 Innovative ancillary services
20 Re-designing capacity markets
21 Regional markets

22 Time-of-use tariffs
23 Market integration of distributed energy resources
24 Net billing schemes

SYSTEM OPERATION

25 Future role of distribution system operators
26 Co-operation between transmission and distribution system operators

27 Advanced forecasting of variable renewable power generation
28 Innovative operation of pumped hydropower storage

29 Virtual power lines
30 Dynamic line rating

This brief provides an overview of utility-scale stationary battery storage systems -also referred to as front-of-the-meter, large-scale or grid-scale battery storage- and their role in integrating a greater share of VRE in the system by providing the flexibility needed. The brief highlights some examples of large-scale battery storage deployment and the impact of this technology on the power system.

The brief is structured as follows:

I Description

II Contribution to power sector transformation

III Key factors to enable deployment

IV Current status and examples of ongoing initiatives

V Implementation requirements: Checklist

I. DESCRIPTION

The growing share of VRE sources, such as solar and wind, calls for a more flexible energy system to ensure that the VRE sources are integrated in an efficient and reliable manner. Battery storage systems are emerging as one of the potential solutions to increase system flexibility, due to their unique capability to quickly absorb, hold and then reinject electricity. According to the Energy Storage Association of North America, market applications are commonly differentiated as: in-front of the meter (FTM) or behind-the-meter (BTM).

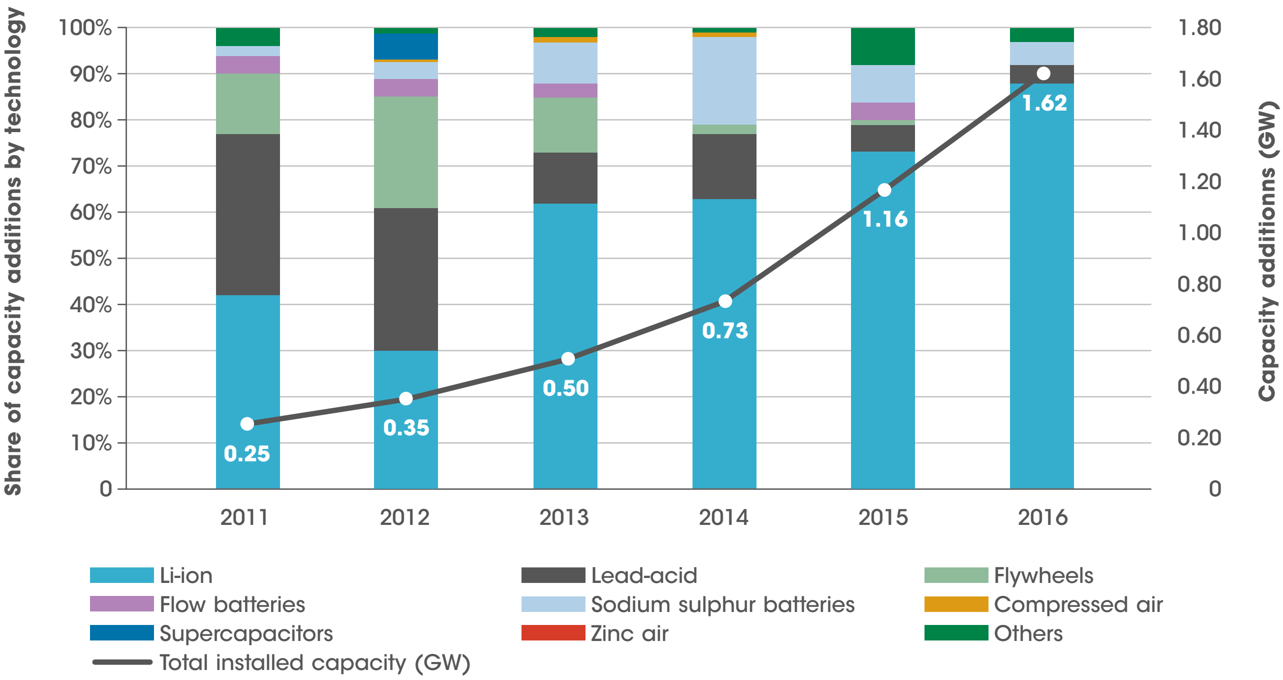
FTM batteries are connected to distribution or transmission networks or in connection with a generation asset. They provide applications required by system operators, such as ancillary services or network load relief. BTM batteries are interconnected behind the utility meter of commercial, industrial or residential customers, primarily aiming at electricity bill savings through demand-side management (ESA, 2018). This brief focuses on how utility-scale stationary battery storage systems – also referred to as front-of-the-meter, large-scale or grid-scale battery storage – can help effectively integrate VRE sources into the power system and increase their share in the energy mix.

Unlike conventional storage systems, such as pumped hydro storage, batteries have the advantage of geographical and sizing flexibility and can therefore be deployed closer to the location where the additional flexibility is needed and can be easily scaled. Deployment of pumped hydro storage, on the other hand, requires specific geological conditions (*i.e.* mountains and water).

Utility-scale battery storage systems have a typical storage capacity ranging from around a few megawatt-hours (MWh) to hundreds of MWh. Different battery storage technologies, such as lithium-ion (Li-ion), sodium sulphur and lead acid batteries, can be used for grid applications. However, in recent years, most of the market growth has been seen in Li-ion batteries.

Figure 1 illustrates the increasing share of Li-ion technology in large-scale battery storage deployment, as opposed to other battery technologies, and the annual capacity additions for stationary battery storage. In 2017, Li-ion accounted for nearly 90% of large-scale battery storage additions (IEA, 2018).

Figure 1: Increasing share of Li-ion in annual battery storage capacity additions globally

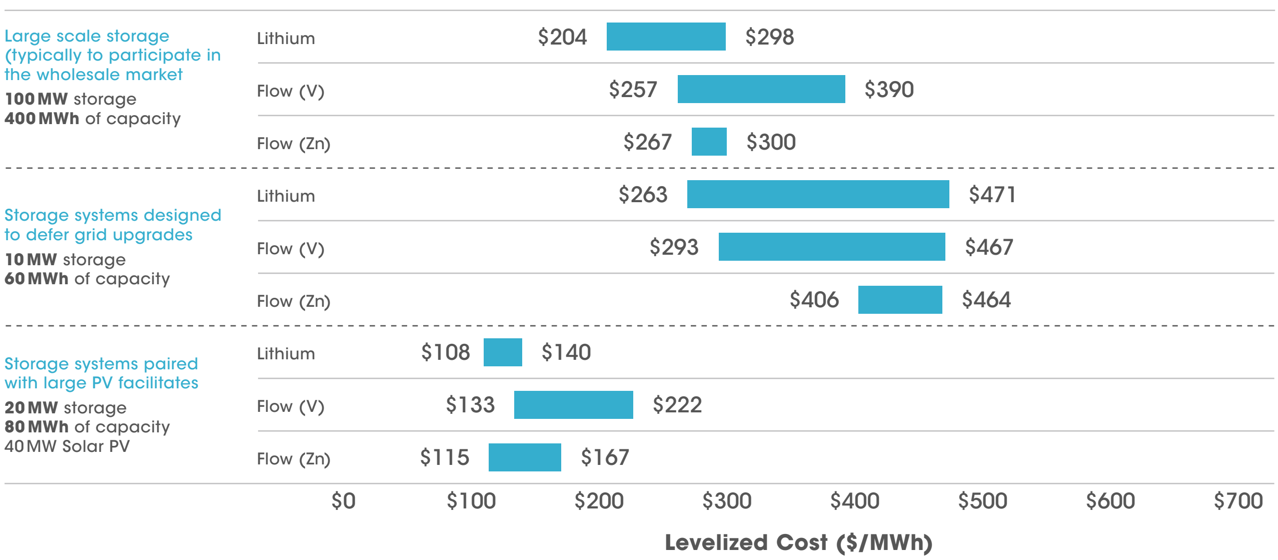


Note: GW = gigawatt
Source: IEA (2018); Sandia Corporation (2018)

The increasing share of Li-ion batteries in storage capacity additions has been largely driven by declining costs in Li-ion technology, which has in turn been driven by the ramp-up in production to meet growing demand for electric vehicles.

Figure 2 depicts the current levelised cost of three storage technologies (Li-ion, flow battery–vanadium, flow battery–zinc bromide) for three battery sizes, aimed at different applications:

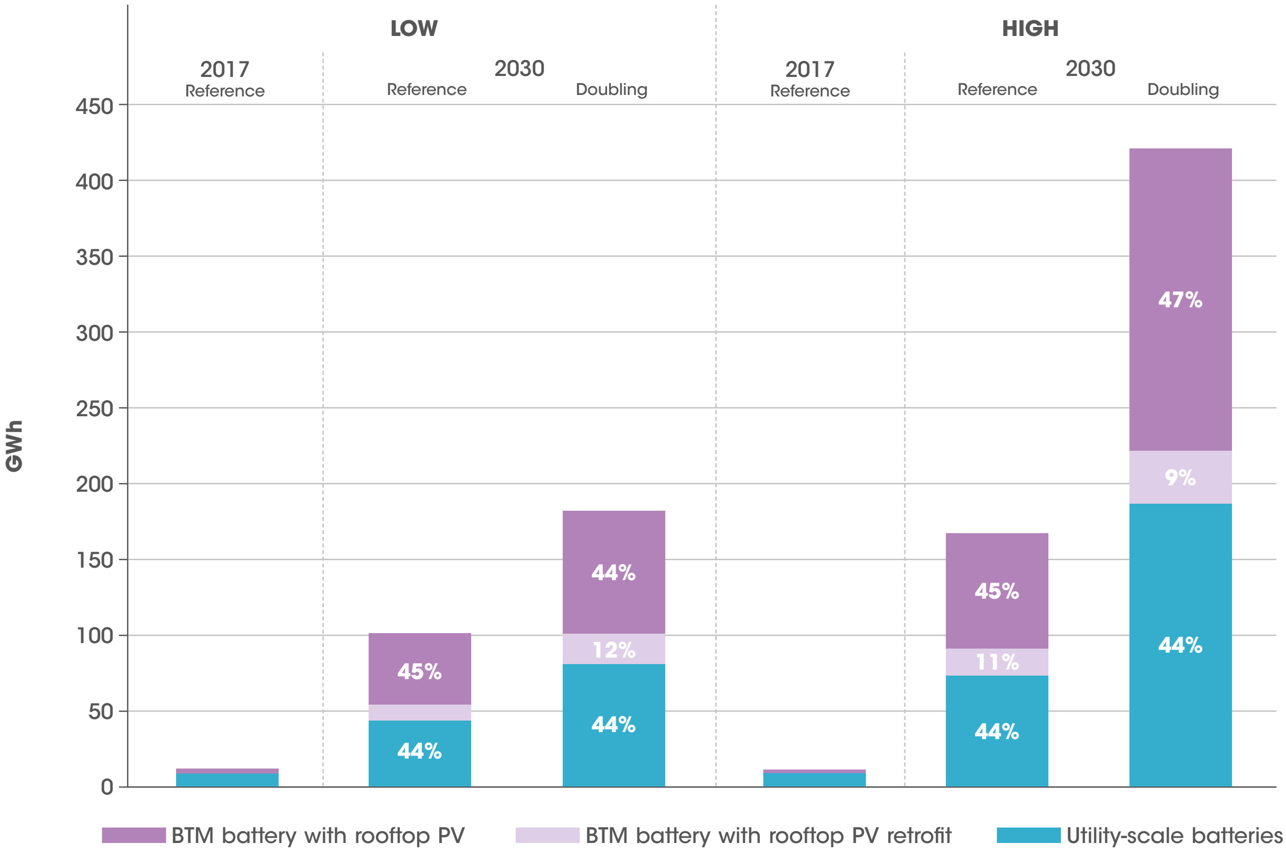
Figure 2: Comparison of levelised cost of storage (USD/MWh)



Note: Flow (V) = flow battery-vanadium; Flow (Zn) = flow battery-zinc bromide
Source: Lazard (2018)

Although large-scale stationary battery storage currently dominates deployment in terms of energy storage capacity, deployment of small-scale battery storage has been increasing as well. Figure 3 illustrates different scenarios for the adoption of battery storage by 2030. "Doubling" in the figure below refers to the scenario in which the stationary battery storage increases in response to the requirement to double renewables in the global energy system by 2030.

Figure 3: Stationary battery storage's energy capacity growth, 2017–2030

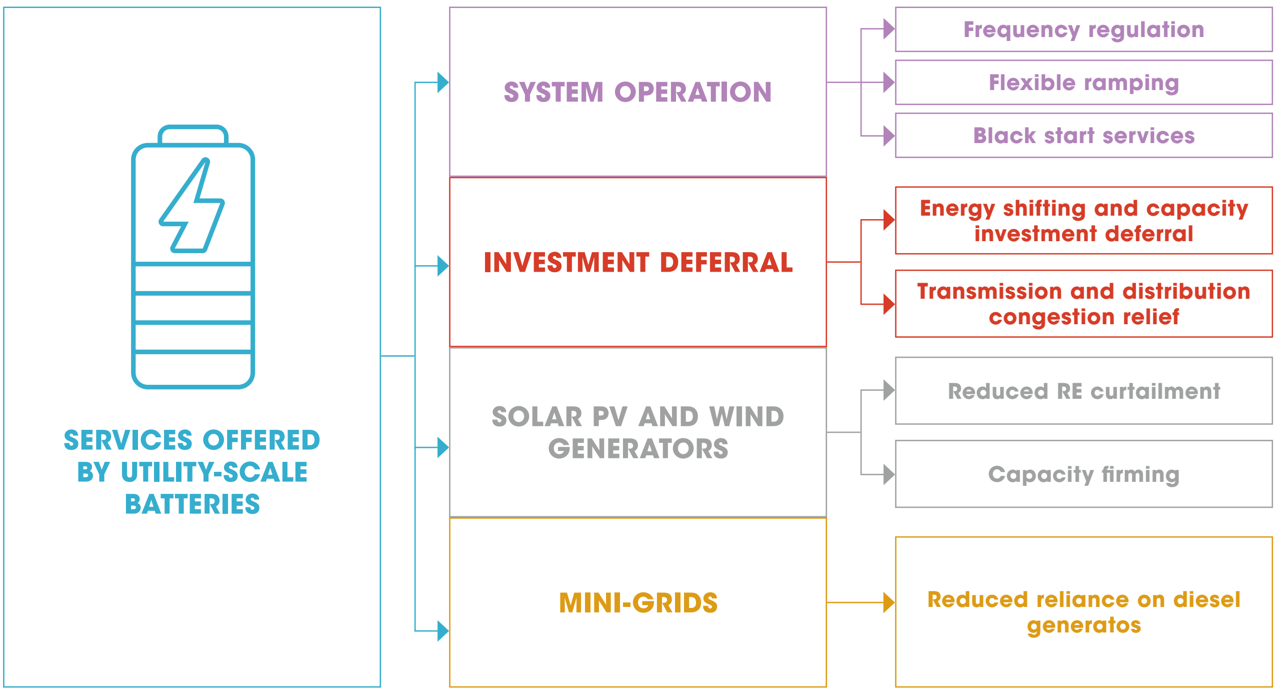


Note: GWh = gigawatt-hour; PV = photovoltaic; BTM = behind-the-meter
Source: IRENA, 2017

II. CONTRIBUTION TO POWER SECTOR TRANSFORMATION

Utility-scale battery storage systems will play a key role in facilitating the next stage of the energy transition by enabling greater shares of VRE. For system operators, battery storage systems can provide grid services such as frequency response, regulation reserves and ramp rate control. It can also defer investments in peak generation and grid reinforcements. Utility-scale battery storage systems can enable greater penetration of variable renewable energy into the grid by storing the excess generation and by firming the renewable energy output. Further, particularly when paired with renewable generators, batteries help providing reliable and cheaper electricity in isolated grids and to off-grid communities, which otherwise rely on expensive imported diesel for electric generation. Figure 4 summarises the key services offered by utility-scale batteries.

Figure 4: Services offered by utility-scale battery storage systems



Services provided for system operation

Utility-scale battery storage systems can provide key services that are needed for the operation of a system with high shares of VRE. These services include frequency regulation, flexible ramping and black start services, which are outlined below.

Frequency regulation

An imbalance between the power supply and the power demand can lead to a dip or a rise in grid frequency beyond the specified limits. Traditionally, thermal power plants have provided frequency control services. This can be inefficient and costly as it requires many generation plants to be either on standby or forced to run at capacity levels that do not use fuel efficiently, thereby increasing electricity costs. Utility-scale battery storage systems can provide frequency regulation services. As opposed to conventional plants that can take several seconds to minutes to respond to system operators' instructions, battery storage systems can typically respond to such requirements within milliseconds.

Tesla, a US company, commissioned the world's largest Li-ion battery storage capacity of 100 MW/129 MWh at the 315 MW Hornsdale Wind Farm in South Australia to provide contingency reserves and frequency regulation services to the South Australia grid. A report from the Australian Energy Market Operator states that frequency regulation services provided by this project are both rapid and precise, being comparable to services provided by conventional synchronous generation units (AEMO, 2018).

In the United States, Federal Electricity Regulatory Commission (FERC) Order 755 has mandated a separate compensation structure for fast-acting resources such as batteries, than for slower-acting conventional resources. This incentivised the use of battery storage systems to provide frequency regulation. This rule has already been adopted by various system operators in the United States, including PJM (Pennsylvania New Jersey Maryland), MISO (Midcontinent Independent System Operator), NYISO (New York Independent System Operator) and CAISO (California Independent System Operator), thus providing incentives to large-scale battery storage project developers (NY-BEST, 2016).

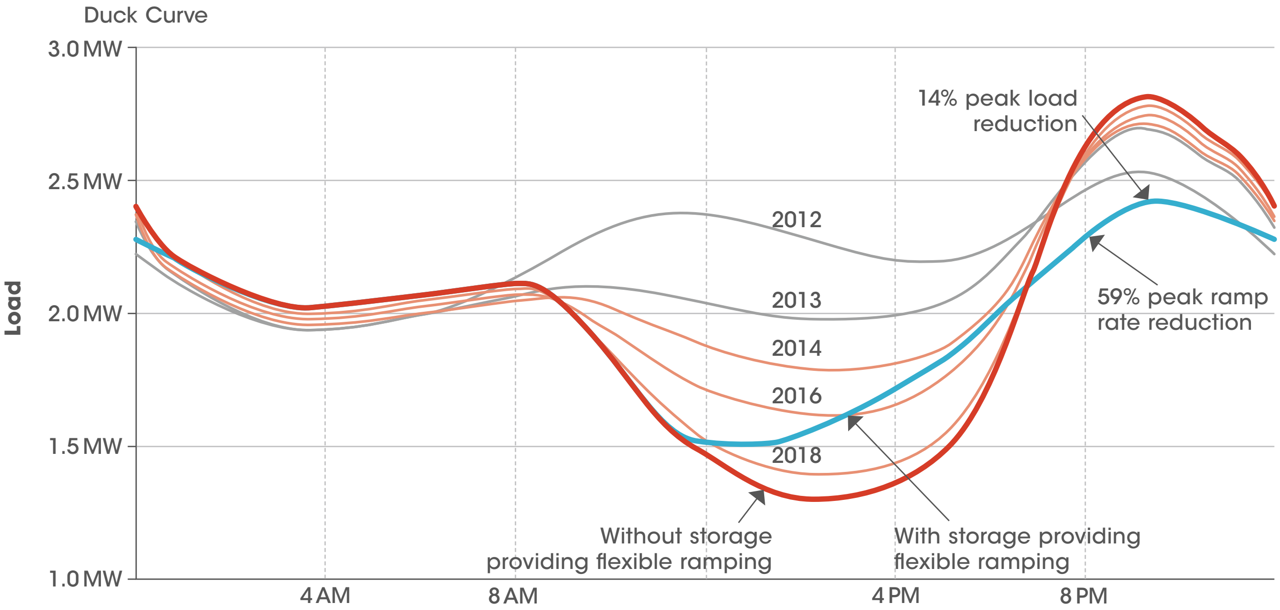
Similarly, the 2016 auction in the United Kingdom, National Grid, the transmission system operator, contracted 200 MW of battery storage capacity to enhance the frequency response capability over the next four years. Even though the tender for this project was technology neutral, battery storage systems won the entire capacity on offer as they were considered most suited for this application (KPMG, 2016).

Flexible ramping

When VRE penetration, and more specifically solar photovoltaic (PV) penetration, starts to increase, the shape of the load curve changes dramatically into the so-called solar duck curve. The duck curve is characterised by very high ramping requirements and was first prominent in the Californian power system. The system is required to ramp downwards in the morning when solar generation increases and ramp upwards in the evening when solar generation decreases and demand increases.

Flexible technologies such as utility-scale batteries would be suitable to help meet these ramping requirements and flatten the duck curve. For instance, California is fostering the deployment of energy storage systems and aiming to reach 1.3 gigawatts (GW) of newly installed storage by 2020 (California Energy Commission, 2018). Since 2016, CAISO has installed 80 MW of new battery storage systems, yielding a total of around 150 MW, including the largest Li-ion facility in North America at the time (30 MW/120 MWh), located in Escondido and owned by San Diego Gas and Electric utility (Davis, 2018). Figure 5 shows an expected effect on the duck curve of storage providing flexible ramping: 59% peak ramp rate reduction and 14% peak load reduction.

Figure 5: Impact on the duck curve of energy storage providing flexible ramping, using as an example a 3 MW feeder (not the entire CAISO system)



Source: Sunverge (2015)

Black start services

In the event of grid failure, restoration of generation plants requires power to start up again (referred to as "black start"). Typically, this restoration power is provided by diesel generators, which are co-located with the generating plants. Large-scale battery storage systems can be co-located, just like diesel generators, to provide black start services in cases of grid failure. Also, the battery storage systems installed on site could also provide other ancillary services to system operators when not being used to provide black start services. This would provide additional revenue to such battery systems.

Services provided for investment deferral

Energy shifting and capacity investment deferral

Large-scale battery storage systems are well suited to serve as capacity reserves as they can discharge during peak hours, displacing peak-generators and deferring further investment in peaking plants.

In the United States and Europe, large-scale battery storage systems are already being deployed to provide capacity reserves in commercial applications. For example, a 6 MW/10 MWh storage system was developed in Bedfordshire by a British distribution network operator, UK Power Networks, and is currently being operated by demand response software startup Limejump to provide capacity reserves in addition to grid-balancing services to the UK grid (Williams, 2017).

Additionally, most of the several hundred MW of utility-scale energy storage procured in California to date serves the state's four-hour peak capacity needs. The electricity supplier Southern California Edison uses a battery farm of 20 MW capacity to store energy and meet spikes in demand, for example on hot summer afternoons when buildings turn on the air conditioning. The battery is designed to discharge 80 MWh of electricity in four-hour periods (Fehrenbacher, 2017).

Transmission and distribution congestion relief

During peak demand hours, power flow through transmission and distribution networks may exceed the load-carrying capacity of such networks, leading to network congestion. Traditionally, system operators have addressed this issue by investing in distribution and transmission assets to increase their carrying capacity. However, when congestion occurs only in specific situations for a very limited period, investments in reinforcing the entire grid might not be the optimal solution. Instead of overbuilding transmission and distribution systems, energy storage systems located at congestion points can be used as "virtual power lines" to enhance the performance and reliability of the system. Utility-scale battery storage systems, as part of infrastructure, can be used to store energy from renewable energy generation to address peak demand exceeding the network capacity. Additionally, battery storage systems can provide instantaneous response to transmission-distribution network systems to manage any variability caused by generation from renewable energy sources.

Batteries could be controlled directly by system operators to provide an instantaneous response during the few hours each year when the existing network substations may be overloaded. Moreover, instead of upgrading the substation capacity from, for example, 10 MW to an oversized 15 MW, as it is generally done, system operators could instead procure the exact incremental amount of storage to meet demand forecasts. For instance, Italy's transmission system operator, Terna, deployed a pilot battery storage project of 35 MW on a part of its 150 kilovolt (kV) grid in Southern Italy for grid congestion management (Terna, 2018). Utility-scale batteries are also used for grid upgrade deferral in California, New York and Texas.

Services provided for VRE generators

Reduced renewable energy curtailment

VRE generators do not have a controllable fixed output, but a fluctuating, non-dispatchable one. Excess renewable energy generation curtailment – in times of high VRE generation and low demand – has been witnessed in some locations, resulting in a missed opportunity to integrate clean electricity into the energy mix. Grid constraints prevent transporting excess renewable energy generation to other regions leading to curtailment. Utility-scale battery storage systems are one of the solutions for reducing renewable energy curtailment. Excess electricity can be stored and then used at peak demand, when most needed.

Another emerging trend in large-scale battery storage is to deploy centralised batteries in a district to store the surplus energy generated by local distributed generation plants, such as rooftop solar PV. These battery storage systems are connected to the distribution network and can be directly controlled by the distribution system operator. The stored electricity can be utilised later when demand exceeds supply in the specific district. Such pilot is being implemented in Walldorf, Germany, with a 100 kW battery system connected to 40 households (GTAI, 2018).

Capacity firming

VRE generation is characterised by variability and uncertainty. Power fluctuations in solar PV generation are mainly caused by cloud movements, and fluctuations in wind power generation are provoked by the variability of wind speed. Coupling a specific VRE generation source with a battery reduces the variability of the power output at the point of grid interconnection, thus facilitating better integration of renewables. The battery storage system can smoothen the output of VRE sources and control the ramp rate to eliminate rapid voltage and power fluctuations in the grid. Further, the smoothening of generation would allow renewable energy generators to increase compliance with their generation schedules and avoid penal charges for any deviation in generation. Generation smoothening would also allow renewable energy generators to take better positions in market-based auctions for energy or capacity because it would increase the certainty and availability of round-the-clock power.

For instance, Acciona Energia has implemented a Li-ion battery storage system at the Barasoain experimental wind farm in Spain. The system comprises a fast response battery with a capacity of 1 MW/0.39 MWh that can maintain 1 MW of power for 20 minutes, and one slow response battery with greater autonomy of 0.7 MW/0.7 MWh that can maintain 0.7 MW for one hour. The batteries will store energy produced by the wind turbine when required (Froese, 2017).

Services provided to mini-grid systems: Reduced reliance on diesel generators

Mini-grid systems on islands or remote communities have typically relied on diesel generators for reliable energy supply. As energy generation from renewables has become cost competitive, their deployment on islands and remote areas is increasing. However, it is difficult to balance variable demand and supply in such remote areas because of the absence of flexible sources of generation. Battery storage systems can help back up the renewable energy supply in such situations and help balance the supply and demand by charging and discharging as needed. This will lead to decreasing dependence on diesel-based power in such systems and an increasing share of renewable energy generation.

In Hawaii, almost 130 MWh of battery storage systems have been implemented to provide smoothening services for solar PV and wind energy in addition to providing grid services. More battery storage systems are planned (Hawaii Electric Company, 2018). Further, the island of Ta'u in American Samoa used to rely on diesel to supply all its electricity, until Tesla installed a 1.4 MW solar and 0.75 MW/6 MWh storage system in 2016. Now the island almost exclusively uses solar energy, sometimes without turning on the diesel generator for months for supplemental electric generation (Muoio, 2016)

Potential impact on power sector transformation

Increased deployment of utility-scale battery storage systems can help integrate greater shares of VRE into the power system and realise cost savings for multiple stakeholders. Renewable energy generators can increase revenues that would have otherwise been lost owing to curtailment. Islands and off-grid communities can further save on high fuel costs and reduce their fossil fuel dependency. Examples of such benefits are shown below

- A high-level demonstration study for mitigating transmission congestion using a 4 MW/40 MWh battery storage system showed that NYISO could save up to **USD 2.03 million in fuel costs and reduce almost 400 hours of congestion (IEEE, 2017)**.
- A draft study commissioned by the State of New York estimated over **USD 22 billion in savings** if the state deployed about 11 500 MW of energy storage in lieu of traditional grid solutions by 2025 (NYSERDA, 2018).
- PJM has deployed energy storage systems that are providing cost-efficient frequency response and reducing the use of fossil fuel generation for ancillary services. PJM has forecasted that a 1**0–20% reduction in the procurement of frequency response capacity could result in savings of USD 25–50 million** for its consumers (HDR, 2017).
- In 2014, Aquion Energy, a US energy storage system provider, completed the installation of a 1 MWh battery system as part of an off-grid solar microgrid at Bakken Hale on the island of Hawaii. This is expected to **reduce the fossil fuel usage** of the local community in Bakken Hale **by 97%** (ESA, 2014).
- In Martinique, the output of a solar PV farm will be supported by a 2 MWh energy storage unit, so that electricity will be injected into the grid at constant power, limited to 40% of the rated PV power. This will establish **solar PV as a predictable and reliable part of the island's energy mix**, with no need for additional back-up generation to compensate for the intermittent nature of renewable energy sources (DOE Global Energy Storage Database, 2019).

III. KEY FACTORS TO ENABLE DEPLOYMENT

Numerous factors are limiting the growth of the large-scale battery storage market worldwide. Utility-scale battery storage technologies have high upfront costs. Further, since utility-scale battery storage is an emerging technology, key stakeholders such as governments, regulators, system operators, generators and financiers are not completely aware of its benefits and case studies. As a consequence, they have not fully updated planning, valuation, procurement and interconnection processes to accommodate this new asset class.

Also, regulatory constraints, due to regulation not taking this technology into account, further limit the revenue streams and deployment of utility-scale batteries. It is therefore important to tackle these barriers by addressing them through government initiatives, incentive programmes and knowledge dissemination. This section lists some of the key enabling factors that could lead to faster deployment of large-scale battery storage systems.

Reducing upfront investment costs and the economic viability gap

Upfront investment costs are still a barrier to the growth of the large-scale battery storage market. Despite the significant reduction in cost of several battery technologies, the upfront costs for deploying large-scale battery storage systems remain high for most stakeholders. Local and national governments can stimulate demand by providing subsidies to battery storage owners, which would scale up deployment and reduce the upfront cost burden.

In most cases, although the monetisable and non-monetisable benefits combined outweigh the costs, the monetisable benefits are less than the costs, making the project economically infeasible for the project developer or owner. The difference between the cost and the monetisable benefits, or the economic viability gap, if greater than zero, might be due to high storage capital costs or unfavourable market mechanisms (IRENA, forthcoming).

Policy incentives to make up for the economic viability gap of electricity storage projects could be similar to those used to support VRE deployment in its early stages of development. These incentives could include capacity payment, grants, feed-in-tariffs, peak reduction incentives, investment tax credits or accelerated depreciation (IRENA, forthcoming).

In the United States, incentives provided under the American Recovery and Reinvestment Act of 2009 opened a new source of financing for large-scale battery storage owners. From 2009 to 2014, 124 grid-scale energy storage projects were commissioned to demonstrate several principal application categories, including battery storage for utility load shifting, ancillary services and distributed storage for grid support (Hart & Sarkissian, 2016).

Creating a conducive regulatory framework to value energy storage

Regulation needs to be adapted to take into account this new technology and market player, as well as the services it can provide to the system.

The existing grid system is designed to balance supply and demand, separating generators and load as distinct entities. In electricity storage, the roles of injecting energy and of absorbing or consuming energy overlap, making it difficult for storage to fit into existing market frameworks (IRENA, forthcoming). Clear regulations defining the ownership and operating models can enable a wide range of revenue streams for storage providers. This can include participation in wholesale electricity markets or the sale of frequency response or ramping services to system operators.

Energy storage plays a key role in the transition towards a carbon-neutral economy and has been addressed within the European Union's "Clean energy for all Europeans package". The role of batteries in balancing power grids and saving surplus energy represents a concrete means of improving energy efficiency and integrating more renewable energy sources into electricity systems. Batteries will also enhance energy security and create a well-functioning internal market with lower prices for consumers (European Commission, 2018). The "Clean energy for all Europeans package" intends to define a new regulatory framework that allows energy storage to compete fairly with other flexibility solutions, such as demand response, interconnections, grid upgrades and flexible generation.

At the national level, the electricity regulator in the United Kingdom, Ofgem, released the "Smart systems and flexibility plan" in July 2017. This plan aims to remove barriers for smart technologies such as energy storage. Some of the targeted interventions include:

- defining energy storage as a subset of the generation asset class
- modifying licence charges to exempt storage systems from final consumption levies
- bringing clarity to the co-location of storage with renewable energy generation plants without impacting existing agreements such as "Contracts for difference and feed-in-tariffs" (Ofgem, 2017).

Since 2011 in the United States, FERC Order 755 has mandated that regional transmission organisations and independent system operators pay storage asset owners for providing ancillary services such as frequency regulation (Wesoff, 2013). Further, in February 2018, FERC passed Order 841, requiring that wholesale market operators allow storage to provide every market product that the resources are physically capable of providing, namely capacity, energy and ancillary services. Within the subsequent nine months, each regional transmission organisation and independent system operator was required to prepare a plan for revising the tariff structure to establish a participation mode for energy storage (FERC, 2018). Further, FERC Order 845 has revised the definition of "generating facility" to include electricity storage explicitly. The order revises interconnection rules and protocols for storage. It also includes a set of provisions that should enable energy storage to utilise spare capacity on the transmission system (Maloney, 2018).

It is also essential that energy storage resources are evaluated and integrated in planning procedures, along with traditional grid investments and generation.

Establishing pilot projects and disseminating knowledge

For any emerging technology such as battery storage, pilot projects are essential in understanding the performance of the technology and producing key learnings for its successful scale-up. Countries without significant deployment of utility-scale battery storage projects can fund pilot programmes to evaluate the technical performance as well as assess different business models for battery storage systems. For example, a South African company has secured a grant from the US Trade and Development Agency to develop a pilot project that demonstrates the performance of an energy storage system. The project will test the performance of a large-scale energy storage system under South Africa's electric grid conditions (ESI Africa, 2017).

Another innovative pilot for mobile storage is being conducted in New York City: Consolidated Edison, a New York utility, is building a 1 MW/4 MWh demonstration project in the city, in collaboration with NRG Energy, to demonstrate multiple uses for battery systems. These batteries will be housed on tractor trailers and will be moved near distribution nodes experiencing peak load to relieve distribution constraints (Maloney, 2017).

IV. CURRENT STATUS AND EXAMPLES OF ONGOING INITIATIVES

Total battery capacity in stationary applications could increase from a current estimate of 11 GWh to between 100 GWh and 167 GWh in 2030 in the IRENA's REmap[1] reference case and to as much as 181–421 GWh in the REmap doubling case[2]. This represents a nine- to 15-fold increase over the present in the REmap reference case and a 17- to 38-fold increase in the REmap doubling case.

Utility-scale battery storage systems are mostly being deployed in Australia, Germany, Japan, the United Kingdom, the United States and other European nations. Apart from these countries, several island and off-grid communities have invested in large-scale battery storage to balance the grid and store excess renewable energy. Energy storage deployments in emerging markets are expected to increase by over 40% year on year until 2025, resulting in approximately 80 GW of new storage capacity (IFC, 2017). The following table provides some key facts about global large-scale battery storage installations.

Table 1 Key facts about large-scale battery storage

Description	Key facts
Key regions where large-scale batteries are used (2017)	Australia, China, Germany, Italy, Japan, Republic of Korea, the United Kingdom and the United States
Global installed capacity of large-scale battery storage systems	10 GW (IRENA, 2017)
Main services currently provided	• Ancillary services, such as frequency response and voltage support • Capacity reserve • Renewable energy capacity firming and curtailment reduction • Reliable power supply to isolated grids • Deferral of transmission and distribution upgrades
Most established large-scale battery storage technology	• Currently, Li-ion batteries represent over 90% of the total installed capacity for large-scale battery storage (IEA, 2017) • Costs fell by 80% from 2010 to 2017 (IRENA, 2017)
Largest capacity project to date	In November 2018, PG&E in California awarded the world's two largest battery contracts to date, at 300 MW/2 270 MWh and 182 MW/730 MWh (Bade, 2018).
Examples of battery manufacturers	BYD, GS Yuasa, Hitachi, Kokam, LG Chem, NEC Energy, NGK, Panasonic, Saft, Samsung SDI, Sony, Toshiba

1 IRENA's global REmap roadmap in its "REmap Scenario" analyses the deployment of low-carbon technologies, largely based on renewable energy and energy efficiency, to generate a transformation of the global energy system with the goal of limiting the rise in global temperature to below 2°C above pre-industrial levels by the end of the century

2 The "doubling" scenario refers to the scenario in which the stationary battery storage increases relatively in response to meet the requirement of doubling renewables in the global energy system by 2030.

Some case studies representing different applications of large-scale battery storage systems across the globe are provided below.

Table 2 Case studies of different applications of large-scale battery storage systems

Utility-scale battery	Location	Service provided	Description
Tesla 100 MW/ 129 MWh Li-ion battery storage project at Hornsdale Wind Farm	South Australia, Australia	**Frequency regulation** **Capacity firming**	The battery is intended to provide contingency reserves and ancillary services to the Southern Australia grid (Brakels, 2018).
STEAG's 90 MW/120 MWh battery storage project	Germany	**Frequency regulation**	German energy company STEAG has installed an aggregated capacity of 90 MW/120 MWh battery storage at six different sites in Germany, each having a battery storage capacity of 15 MW/20 MWh. Batteries are connected to the grid at 10 kV and are intended to provide primary frequency control reserve for 30 minutes according to the requirements of the transmission system operator (STEAG GmbH, 2017).
38.4 MW/250 MWh sodium-sulphur battery by Terna	Italy	**Grid investment deferral** **Reduced RE curtailment**	Italy had an excess of wind generation, and the transmission capacity was not enough to transport all this energy to the north of the country, resulting in wind curtailments. In 2015, Terna installed the battery system to absorb the wind energy and use it during later periods with low wind demand, avoiding the need to invest in new transmission capacity. Additionally, this battery can provide services such as primary and secondary reserves, load balancing and voltage control (NGK, 2019).
NGK Insulators 34 MW/204 MWh sodium-sulphur battery storage system	Rokkasho, Aomori, Japan	**Capacity firming** **Reduced RE curtailment** **Ancillary services**	A 34 MW/204 MWh battery storage system was connected to a 51 MW wind farm in northern Japan. The batteries will store the excess renewable energy produced and sell it during peak hours. Further, the batteries will provide frequency regulation and serve as spinning reserves (IRENA, 2015).
1.5 MWh battery + 270 kW solar PV project implemented by Secretariat of the Pacific Community	Yap State, Federated States of Micronesia	**Reduced reliance on diesel generators in mini-grids**	A 1.5 MWh battery system, combined with a cumulative solar PV capacity of 270 kW was deployed over five islands of Yap State, encompassing ten mini-grids. The intended application provides energy access in some areas and displaces costly diesel generation in others (IRENA, 2015).
Low-carbon Li-ion battery in Glassenbury (40 MW) and Cleator (10 MW)	United Kingdom	**Frequency regulation**	These two projects were awarded during the UK auction in 2016 to provide enhanced frequency regulation. Glassenbury has an annual production of 20 MWh, while Cleator produces 7 MWh. Together they provide a quarter of the total enhanced frequency regulation capacity in the United Kingdom and help stabilise the frequency in the grid (Low Carbon, 2019).
AES-SDG&E 30 MW/120 MWh Li-ion battery storage project	California, United States	**Capacity firming** **Reduced RE curtailment** **Capacity investment deferral**	The US utility San Diego Gas & Electric developed a 30 MW/120 MWh Li-ion battery storage project near one of its substations in Escondido to store excess renewable energy production in the state and also serve as a capacity reserve (SDG&E, 2017).

Utility-scale battery	Location	Service provided	Description
2 MW/6 MWh battery storage in San Juan Capistrano	California, United States	**Grid investment deferral**	The battery system offsets the peak demand overload and avoids distribution upgrades. Additionally, this battery can participate in other ancillary services thanks to its control system (Greensmith, 2016).
Renewable Energy Systems and Utility of Ohio's 4 MW/2.6 MWh battery storage project	Columbus, Ohio, United States	**Frequency regulation**	Driven by FERC Order 755, which mandates that independent system operators pay storage providers for the performance of their systems, Renewable Energy Systems, a United Kingdom-based firm, built a 4 MW/2.6 MWh battery storage system to provide frequency regulation services to PJM, a regional transmission operator in the United States (RES, 2017).

RENEWABLE ENERGY POWER GRID

V. IMPLEMENTATION REQUIREMENTS: CHECKLIST

TECHNICAL REQUIREMENTS

Hardware:

- Widespread adoption of utility-scale batteries in power systems.

Software:

- Battery management software to protect the battery and act as a site controller to implement the charging and discharging algorithms

POLICIES NEEDED

Strategic policies could include:

- Incentives to make up for the economic viability gap of electricity storage projects
- Inclusion of energy storage solutions in long-term capacity expansion plans
- Funding for pilot or demonstration projects and dissemination of learnings from case studies

REGULATORY REQUIREMENTS

Wholesale market:

- Allow large-scale battery storage systems to participate in ancillary services markets and be remunerated accordingly for all the services they can provide to support the system
- Develop accounting, billing and metering methods for large-scale grid-connected battery storage systems
- Incentivise long-term contracts to have a clearly defined revenue stream over the amortisation period of the project

Transmission and distribution system:

- Allow large-scale battery storage systems to participate in ancillary services markets and be remunerated accordingly for all the services they can provide to support the system
- Deploy large-scale battery storage systems as a solution to reduce overall investments in generating capacity and network reinforcement

STAKEHOLDER ROLES AND RESPONSIBILITIES

Regulators:

- Include storage batteries in the long-term plans of the system expansion, along with traditional grid and generation investments
- Define clear regulations for the ownership and operating models of storage systems, to enable a wide range of revenue streams

ACRONYMS AND ABBREVIATIONS

CAISO	California Independent System Operator
FERC	Federal Electricity Regulatory Commission
Li-ion	lithium-ion
MISO	Midcontinent Independent System Operator
NYISO	New York Independent System Operator
PJM	Pennsylvania New Jersey Maryland
PV	photovoltaic
VRE	variable renewable energy

UNITS OF MEASUREMENT

GW	gigawatt
GWh	gigawatt-hour
kV	kilovolt
kW	kilowatt
MW	megawatt
MWh	megawatt-hour

BIBLIOGRAPHY

AEMO (2018), *Initial Operation of the Hornsdale Power Reserve Battery Storage System,* Australian Energy Market Operator, www.aemo.com.au/-/media/Files/Media_Centre/2018/Initial-operation-of-the-Hornsdale-Power-Reserve.pdf.

Bade, G. (2018), "Storage will replace 3 California gas plants as PG&E nabs approval for world's largest batteries", Utility Dive, www.utilitydive.com/news/storage-will-replace-3-california-gas-plants-as-pge-nabs-approval-forworl/541870.

Brakels, R. (2018), "Tesla big battery's first year", Solar Quotes, www.solarquotes.com.au/blog/tesla-big-battery-first-year.

California Energy Commission (2018), *Tracking Progress – Energy Storage,* California Energy Commision, Sacramento.

Davis, P. (2018), "Bidding Energy Storage Resources (ESR): CAISO – Power Costs, InC (PCI) Blog, https://blog.powercosts.com/2018/01/21/bidding-energy-storage-resources-esr-caiso/.

ESA (2018), "A beginner's Guide to Energy Storage", Energy Storage Association, http://energystorage.org/system/files/resources/slides_completev2.pdf.

ESA (2014), "Providing 100% renewable power to large residence on protected Kona coast", Energy Storage Association, http://energystorage.org/energy-storage/case-studies/providing-100-renewable-power-large-residence-protected-kona-coast.

ESI Africa (2017), "USTDA empowers energy storage system project in South Africa", www.esi-africa.com/regional-news/southern-africa/ustda-energy-storage-system-project/.

European Commission (2018), "Energy storage", European Commission, https://ec.europa.eu/energy/en/topics/technology-and-innovation/energy-storage.

FERC (2018), "News release", Federal Electricity Regulatory Commission, www.ferc.gov/media/news-releases/2018/2018-1/02-15-18-E-1.asp#.WuiqplhubIU.

Fehrenbacher, R. (2017), "Tesla moves beyond electric cars with new California battery farm", The Guardian, www.theguardian.com/sustainable-business/2017/jan/31/tesla-battery-farm-california-energy-elon-musk.

Froese, M. (2017), "Acciona begins operation of hybrid wind & storage plant", Windpower Engineering, www.windpowerengineering.com/business-news-projects/acciona-begins-operation-hybrid-wind-storage-plant.

Greensmith (2016), "Storage simplifies California Distribution System upgrade", Greensmith Energy.

GTAI (2018), *The Energy Storage Market in Germany,* Germany Trade & Invest, www.gtai.de/GTAI/Content/EN/Invest/_SharedDocs/Downloads/GTAI/Fact-sheets/Energy-environmental/fact-sheet-energy-storage-market-germany-en.pdf?v=9.

Hart, D. and A. Sarkissian, (2016), *Deployment of Grid-Scale Batteries in the United States,* US Department of Energy, www.energy.gov/sites/prod/files/2017/01/f34/Deployment%20of%20Grid-Scale%20Batteries%20in%20the%20United%20States.pdf.

Hawaii Electric Company (n.d.), "Energy storage", Hawaii Electric Company, www.hawaiianelectric.com/about-us/innovation/energy-storage.

HDR (2017), *Battery Energy Storage Technology Assessment,* Platte River Power Authority, www.prpa.org/wp-content/uploads/2017/10/HDR-Battery-Energy-Storage-Assessment.pdf.

IEA (2017), *Tracking Clean Energy Progress: 2017,* International Energy Agency, www.iea.org/etp/tracking2017.

IEA (2018), *Energy Storage: Tracking Clean Energy Progress,* International Energy Agency, www.iea.org/tcep/energyintegration/energystorage.

IEEE (2017), "Large scale storage and demand resources – Enabler of transmission delivery?", Institute of Electrical and Electronics Engineers, www.ieee-pes.org/presentations/gm2014/Storage_as_Transmission_Asset_IEEE_Final.pdf.

IFC (2017), *Energy Storage Trends and Opportunities in Emerging Markets*, International Finance Corporation, www.ifc.org/wps/wcm/connect/50085596-4b07-4e66-8105-dc9c8eddd86/7151-IFC-EnergyStorage-report.pdf?MOD=AJPERES&CVID=lC4-k7y.

IRENA (2015), *Case Studies: Battery Storage, International Renewable Energy Agency,* Abu Dhabi, www.irena.org/documentdownloads/publications/irena_battery_storage_case_studies_2015.pdf.

IRENA (2017), *Electricity Storage and Renewables: Cost and Markets to 2030,* International Renewable Energy Agency, Abu Dhabi, www.irena.org/publications/2017/Oct/Electricity-storage-and-renewables-costs-and-markets.

IRENA (2019), *Innovation Landscape for a Renewable-Powered Future: Solutions to Integrate Variable Renewables,* International Renewable Energy Agency, Abu Dhabi, www.irena.org/-/media/Files/IRENA/Agency/Publication/2019/Jan/IRENA_Innovation_Landscape_preview_2019.pdf?la=en&hash=10221885865D12F47747356D9F6290283B205210.

IRENA (forthcoming), *The Electricity Storage Valuation Framework, Part 3: Electricity Storage Use Cases,* International Renewable Energy Agency, Abu Dhabi.

KPMG (2016), "EFR Tender Results", KPMG, London, https://home.kpmg/content/dam/kpmg/uk/pdf/2016/10/kpmg-efr-tender-market-briefing-updated.pdf.

Lazard (2018), *Lazard's Levelized Cost of Storage Analysis – Version 4.0,* Lazard, https://www.lazard.com/media/450774/lazards-levelized-cost-of-storage-version-40-vfinal.pdf.

Low Carbon (2019), "Glassenbury battery storage project", Low Carbon, www.lowcarbon.com/our-portfolio/portfolio-overview/our-projects/glassenbury-storage-park.

Maloney, P. (2017), "How ConEd's mobile battery REV demo could build a new storage business model", Utility Dive, www.utilitydive.com/news/how-coneds-mobile-battery-rev-demo-could-build-a-new-storage-business-mode/437364.

Maloney, P. (2018), "FERC Order 845 opens door a little wider for energy storage", Utility Dive, www.utilitydive.com/news/ferc-order-845-opens-door-a-little-wider-for-energy-storage/521992.

Muoio, D. (2016), "The new Tesla is powering an entire island with solar energy", The Independent, www.independent.co.uk/life-style/gadgets-and-tech/new-tesla-powering-entire-island-with-solar-energy-a7480156.html.

NGK (2019), Campania Region, Italy: NAS Battery used for Investment Deferral, www.ngk.co.jp/nas/case_studies/terna/.

NY-BEST (2016), *Energy Storage Roadmap for New York's Electric Grid,* New York Battery and Energy Storage Technology Consortium, www.ny-best.org/sites/default/files/type-page/39090/attachments/NY-BEST%20Roadmap_2016_Appendices_finalpages.pdf.

NYSERDA (2018), "New York State energy storage", New York State Energy Research & Development Authority, www.nyserda.ny.gov/All%20Programs/Programs/Energy%20Storage.

Ofgem (2017), *Upgrading Our Energy System,* Office of Gas and Electricity Markets, www.ofgem.gov.uk/system/files/docs/2017/07/upgrading_our_energy_system_-_smart_systems_and_flexibility_plan.pdf.

RES (2017), *PJM Frequency Regulation,* Renewable Energy Systems, www.res-group.com/media/2409/frequencyreg_flyer_042517.pdf.

SDG&E (2017), "SDG&E unveils world's largest lithium ion battery storage facility", San Diego Gas & Electric, http://newsroom.sdge.com/clean-innovative/sdge-unveils-world%E2%80%99s-largest-lithium-ion-battery-storage-facility.

Sandia Corporation (2018), "DOE Global Energy Storage Database", Energy Storage Exchange, www.energystorageexchange.org.

STEAG GmbH (2017), "STEAG large scale battery system – 90 MW experience and learnings", STEAG GmbH, https://docs.google.com/viewerng/viewer?url=http://www.eqmagpro.com/wp-content/uploads/2017/06/20170116_ms_ESI2017_Steag.pdf&hl=en.

Sunverge (2015), "Integrated Energy Storage: An Answer to Addressing the "Duck Curve"? Sunverge. www.sunverge.com/integrated-energy-storage-an-answer-to-addressing-the-duck-curve/.

Terna (2018), *The Role of Storage in Grid Management*, Terna, www.terna.it/en-gb/media/newsedeventi/ilruolodellostoragenellagestionedellereti.aspx.

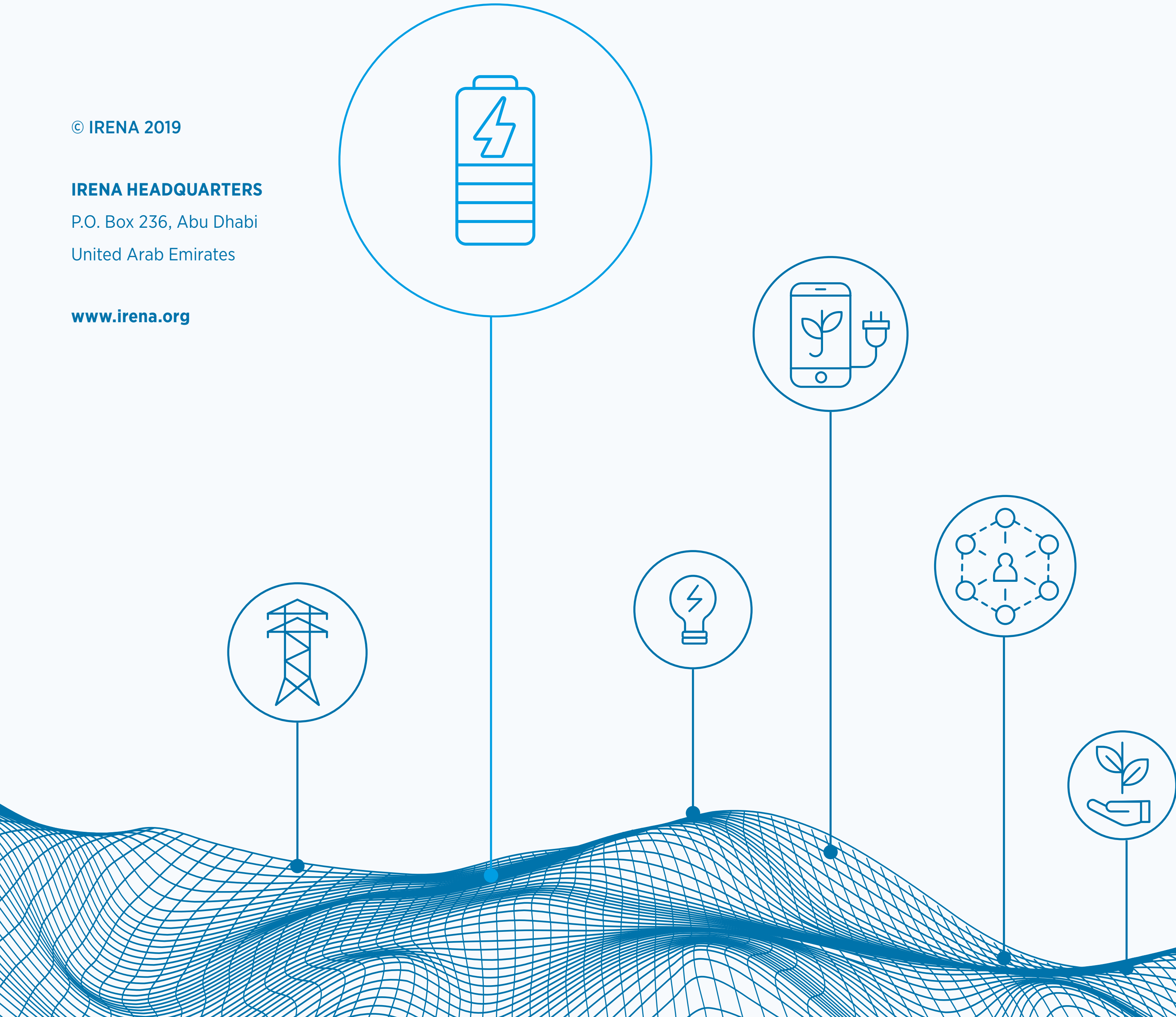
Wesoff, E. (2013), "FERC's energy storage ruling could jump-start big batteries", GTM, www.greentechmedia.com/articles/read/fercs-energy-storage-ruling-could-jump-start-big-batteries#gs.uJz8bJc.

Williams, D. (2017), "'Next generation utility' wins contract for UK's biggest battery", Power Engineering International, www.powerengineeringint.com/articles/2017/05/next-generation-utility-wins-contract-for-uk-s-biggest-battery.html.


100%

IRENA
International Renewable Energy Agency

UTILITY-SCALE BATTERIES
INNOVATION LANDSCAPE BRIEF



IRENA HEADQUARTERS
P.O. Box 236, Abu Dhabi
United Arab Emirates

www.irena.org

IRENA
International Renewable Energy Agency

BEHIND-THE-METER BATTERIES

INNOVATION LANDSCAPE BRIEF

ISBN 978-92-9260-140-9

Citation: IRENA (2019), *Innovation landscape brief: Behind-the-meter batteries*, International Renewable Energy Agency, Abu Dhabi.

ACKNOWLEDGEMENTS

This report was prepared by the Innovation team at IRENA's Innovation and Technology Centre (IITC) with text authored by Arina Anisie and Francisco Boshell with additional contributions and support from Harsh Kanani and Shikhin Mehrotra (KPMG India).

Valuable external review was provided by Patrick Clerens and Jean-Michel Durand (EASE Storage Association), Dirk-Jan Middelkoop (Eneco), along with Michael Taylor, Pablo Ralon, Martina Lyons, Nina Litman-Roventa and Paul Komor (IRENA).

Report available online: www.irena.org/publications
For questions or to provide feedback: publications@irena.org

DISCLAIMER

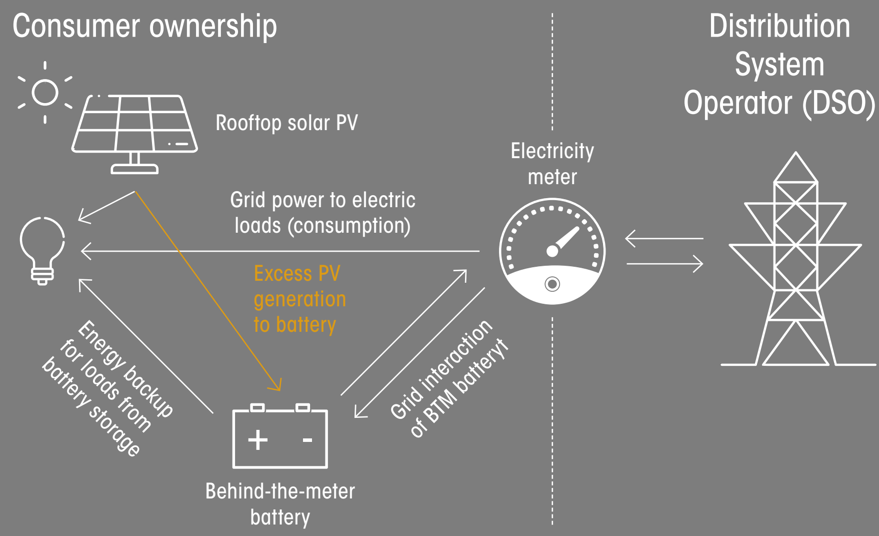
IRENA
International Renewable Energy Agency

1 BENEFITS

BTM batteries can help consumers decrease their electricity bill, through demand-side management.

Increased demand flexibility can unlock the integration of high share of variable renewables in the grid.

Aggregated BTM batteries can provide support for system operation, while also deferring network and peak capacity investment.



2 KEY ENABLING FACTORS

- Reducing upfront cots
- Enabling regulatory framework
- Reducing soft costs, such as connection and permitting costs

3 SNAPSHOT

- 40% of recent rooftop solar photovoltaic (PV) systems in Germany have been installed with BTM batteries
- 21 000 BTM battery systems were installed by 2017 in Australia. The aim is to reach 1 million BTM batteries by 2025.
- 500 kW BTM batteries installed for Morgan Stanley in US reduced peak demand by 20%

WHAT ARE BTM BATTERIES?

Behind-the-meter (BTM) batteries are connected **through electricity meters** for commercial, industrial and residential customers. **BTM batteries range in size from 3 kilowatts to 5 megawatts and are typically installed with rooftop solar PV.**

BEHIND-THE-METER BATTERIES

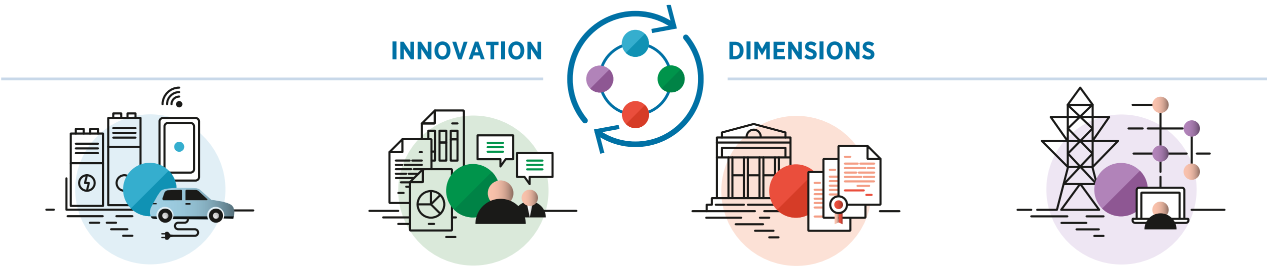
Behind-the-meter (BTM) batteries at the **individual or household level,** combined with the right incentives, can unlock **demand-side flexibility** and ease system integration of electricity from wind and solar **energy.**

ABOUT THIS BRIEF

This brief is part of the IRENA project "Innovation landscape for a renewable-powered future", which maps the relevant innovations, identifies the synergies and formulates solutions for integrating high shares of variable renewable energy (VRE) into power systems.

The synthesis report, *Innovation landscape for a renewable-powered future: Solutions to integrate variable renewables* (IRENA, 2019a), illustrates the need for synergies among different innovations to create actual solutions. Solutions to drive the uptake of solar and wind power span four broad dimensions of innovation: enabling technologies, business models, market design and system operation.

Along with the synthesis report, the project includes a series of briefs, each covering one of 30 key innovations identified across those four dimensions. The 30 innovations are listed in the figure below.



ENABLING TECHNOLOGIES

1 Utility scale batteries
2 Behind-the-meter batteries

3 Electric-vehicle smart charging
4 Renewable power-to-heat
5 Renewable power-to-hydrogen

6 Internet of Things
7 Artificial intelligence and big data
8 Blockchain

9 Renewable mini-grids
10 Supergrids

11 Flexibility in conventional power plants

BUSINESS MODELS

12 Aggregators
13 Peer-to-peer electricity trading
14 Energy-as-a-service

15 Community-ownership models
16 Pay-as-you-go models

MARKET DESIGN

17 Increasing time granularity in electricity markets
18 Increasing space granularity in electricity markets
19 Innovative ancillary services
20 Re-designing capacity markets
21 Regional markets

22 Time-of-use tariffs
23 Market integration of distributed energy resources
24 Net billing schemes

SYSTEM OPERATION

25 Future role of distribution system operators
26 Co-operation between transmission and distribution system operators

27 Advanced forecasting of variable renewable power generation
28 Innovative operation of pumped hydropower storage

29 Virtual power lines
30 Dynamic line rating

This brief provides an overview of behind-the-meter (BTM) battery storage, also referred to as small-scale battery storage, and its role in supporting the integration of VRE in the grid. The brief explains the benefits that BTM batteries can bring both to the power system and to consumers, as well as the role of BTM battery storage in microgrid and mini-grid settings.

The brief is structured as follows:

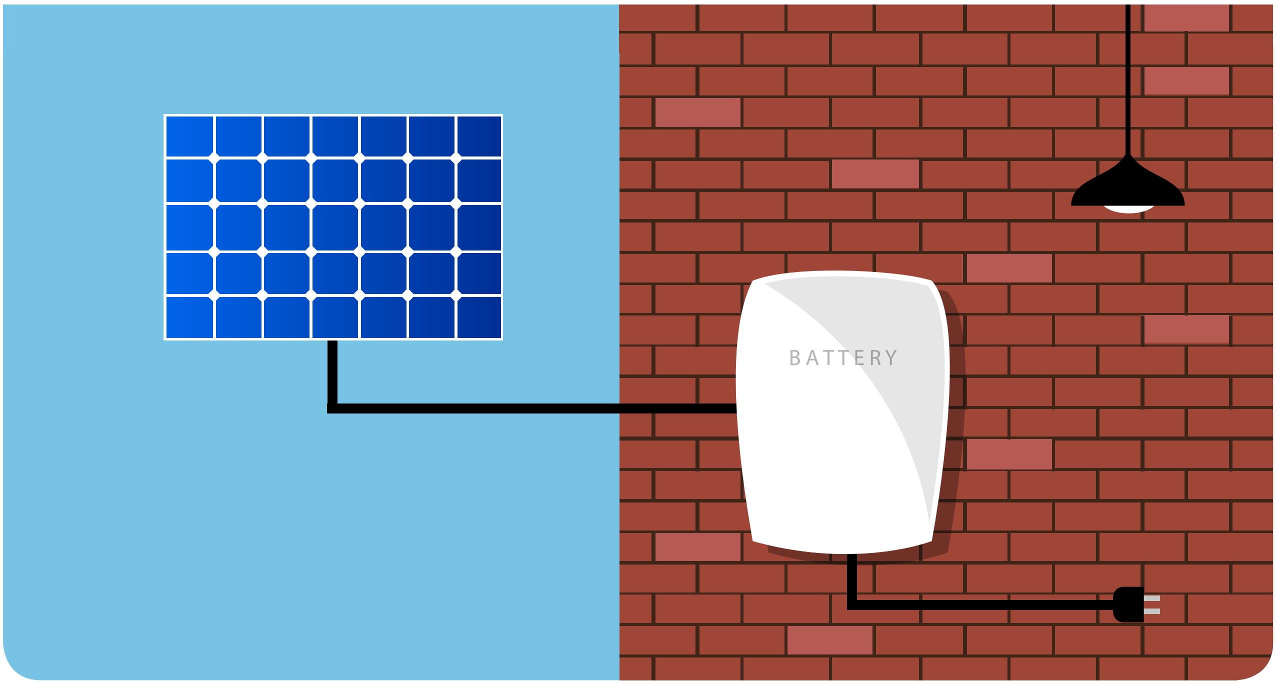
I Description

II Contribution to power sector transformation

III Key factors to enable deployment

IV Current status and examples of ongoing initiatives

V Implementation requirements: Checklist



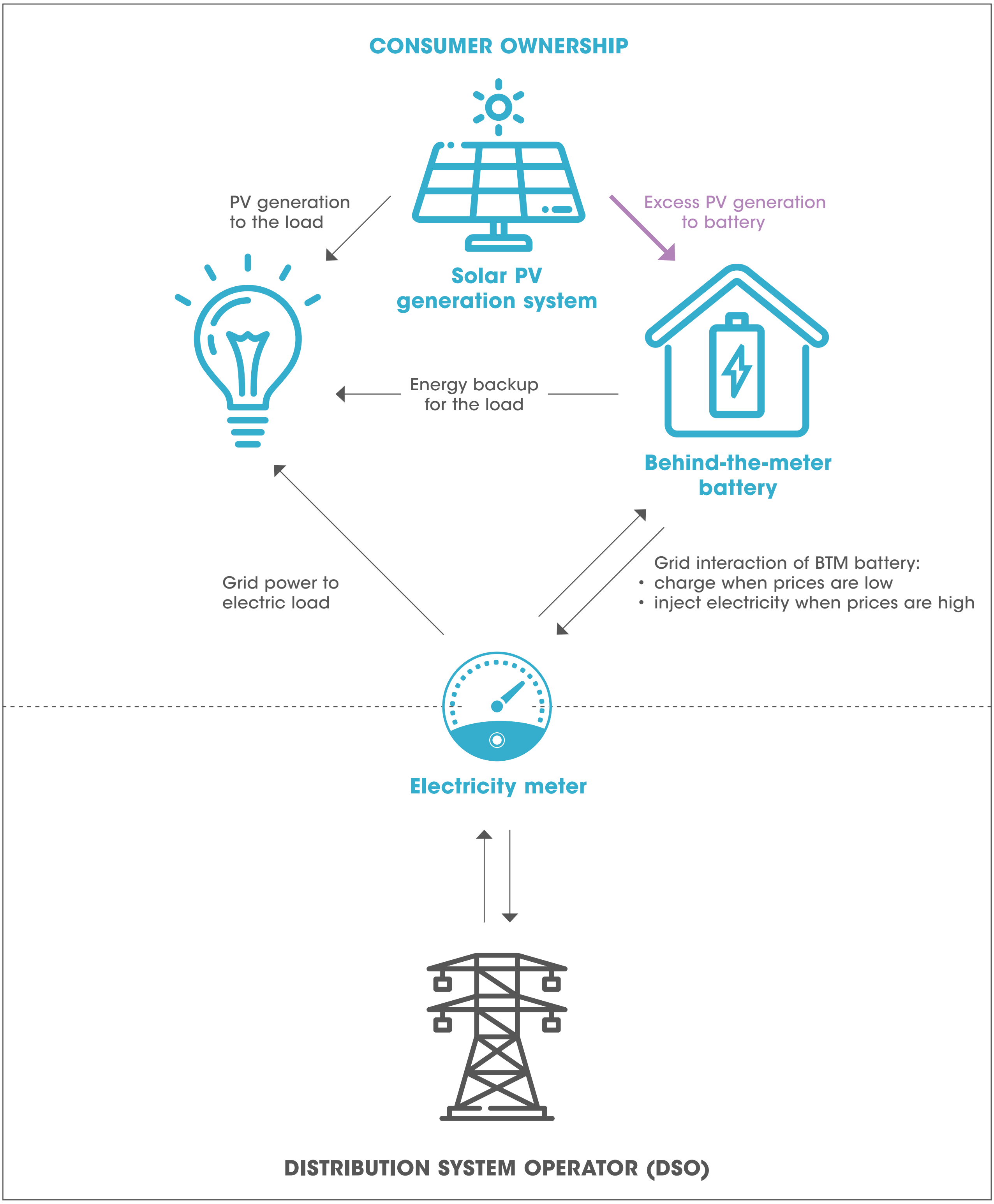
I. DESCRIPTION

Battery storage systems are being deployed at multiple levels of the electricity value chain, including at the transmission, distribution and consumer levels. According to the Energy Storage Association of North America, market applications are commonly differentiated as: in-front of the meter (FTM) or behind-the-meter (BTM). FtM batteries are interconnected to distribution or transmission networks or in connection with a generation asset. They provide applications required by system operators as *e.g.* ancillary services or network load relief. BTM batteries are connected behind the utility meter of commercial, industrial or residential customers, primarily aiming at electricity bill savings (ESA, 2018). This brief focuses on describing the various applications of BTM battery storage also called small-scale stationary batteries. The size of a BTM battery can vary from 3 kilowatts (kW) to 5 megawatts (MW). Typically, residential consumers' batteries can reach 5 kW/13.5 kilowatt-hours (kWh), whereas a battery for a commercial or industrial system is typically 2 MW/4 megawatt-hours (MWh).

The deployment of small-scale battery storage systems is increasing in power systems across the world. For example, approximately 40% of small-scale solar PV systems in Germany have been installed with battery systems in the last few years (IRENA, 2017). In Australia, around 21 000 small-scale battery systems had been installed by 2017, and the goal is to reach 1 million BTM batteries by 2025 (Martin, 2018). This increase has been driven by the falling costs of battery storage technology, due mainly to the growing consumer market and to the development of electric vehicles (EVs) and plug-in hybrid EVs (PHEVs), along with the deployment of distributed renewable energy generation and the development of smart grids.

Battery storage systems deployed at the consumer level – that is, at the residential, commercial and/or industrial premises of consumers – are typically "behind-the-meter" batteries, because they are placed at a customer's facility. They are typically beyond the direct control of the distribution system operator; however, several initiatives exist in which consumers are remunerated for allowing the distribution system operator to withdraw electricity from the battery when needed. Examples include Green Mountain Power's Tesla Powerwall programme in the United States (US) and Eneco's CrowdNett programme in the Netherlands. Figure 1 shows a schematic diagram of a household system using a rooftop solar PV panel and a BTM battery storage system.

Figure 1: Grid-connected BTM energy storage configuration



A BTM battery installed at the consumer's premises can store electricity that either is produced from on-site solar rooftop PV systems (if applicable) or is drawn from the distribution grid, generally when electricity prices are low. This stored electricity can then be used to meet the consumer's electricity needs, or it can be injected back into the distribution grid when electricity prices are high.

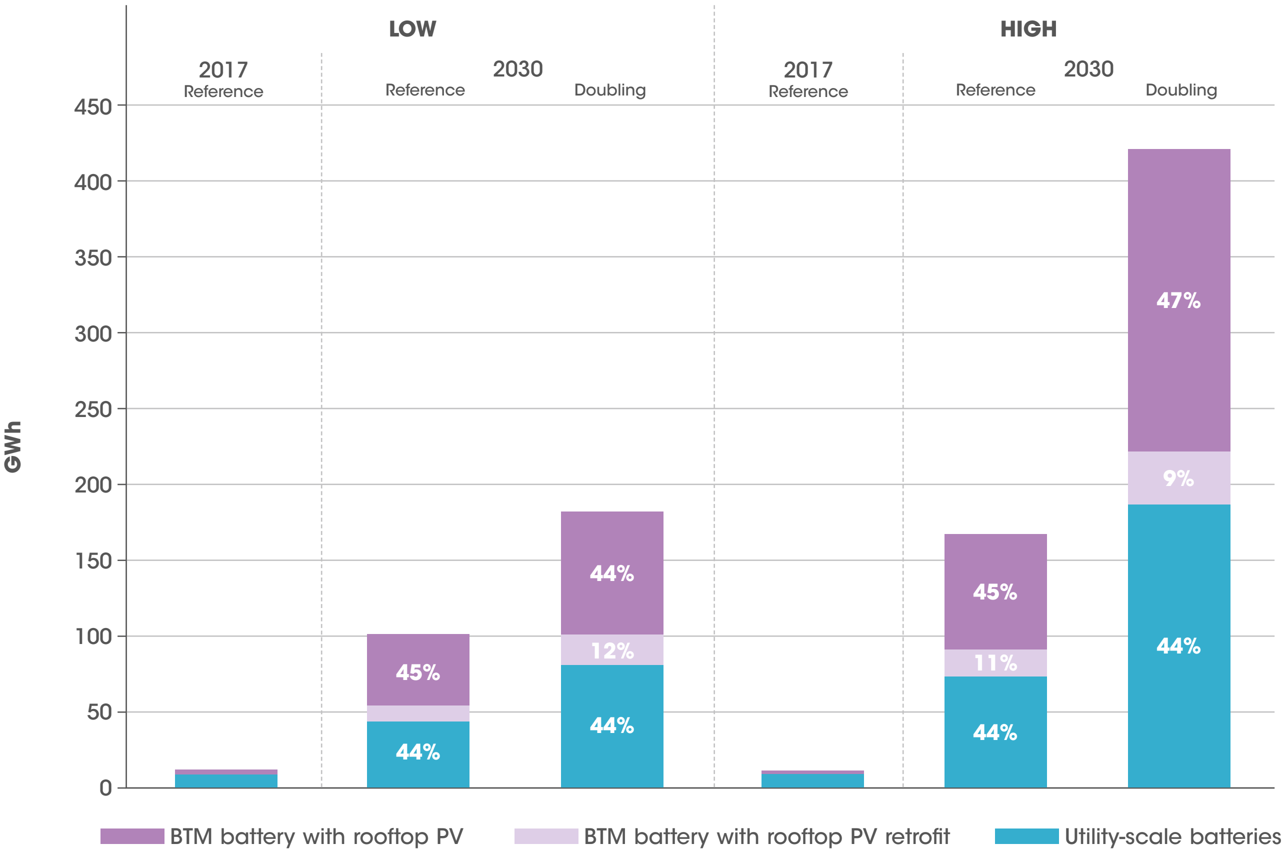
The key value proposition that led to the initial deployment of BTM battery storage systems was their ability to provide back-up power to consumers when a black-out occurs in the system. Consumers and system operators alike are interested in using BTM battery storage systems to improve the resilience of the power supply. These applications have been dominated by lead-acid and lithium-ion battery technologies, the costs of which have been driven down by the deployment of BTM batteries in residential and commercial PV systems, which has enabled cost savings in electricity bills (where time-of-use tariffs are in place). Figure 2 depicts the current levelised cost of three storage technologies (lithium-ion, lead-acid and advanced lead) for different battery sizes and different applications.

Figure 2: Levelised cost of storage comparison (USD/MWh)

Source: LAZARD, 2018

Although currently utility-scale battery systems dominate in terms of energy capacity deployed, the share of small-scale battery systems is expected to increase dramatically, pushed mainly by the deployment of distributed solar PV, as illustrated in Figure 3.

Figure 3: Stationary battery storage's energy capacity growth, 2017–2030



Note: GWh = gigawatt-hour; PV = photovoltaic; BTM = behind-the-meter
Source: IRENA, 2017

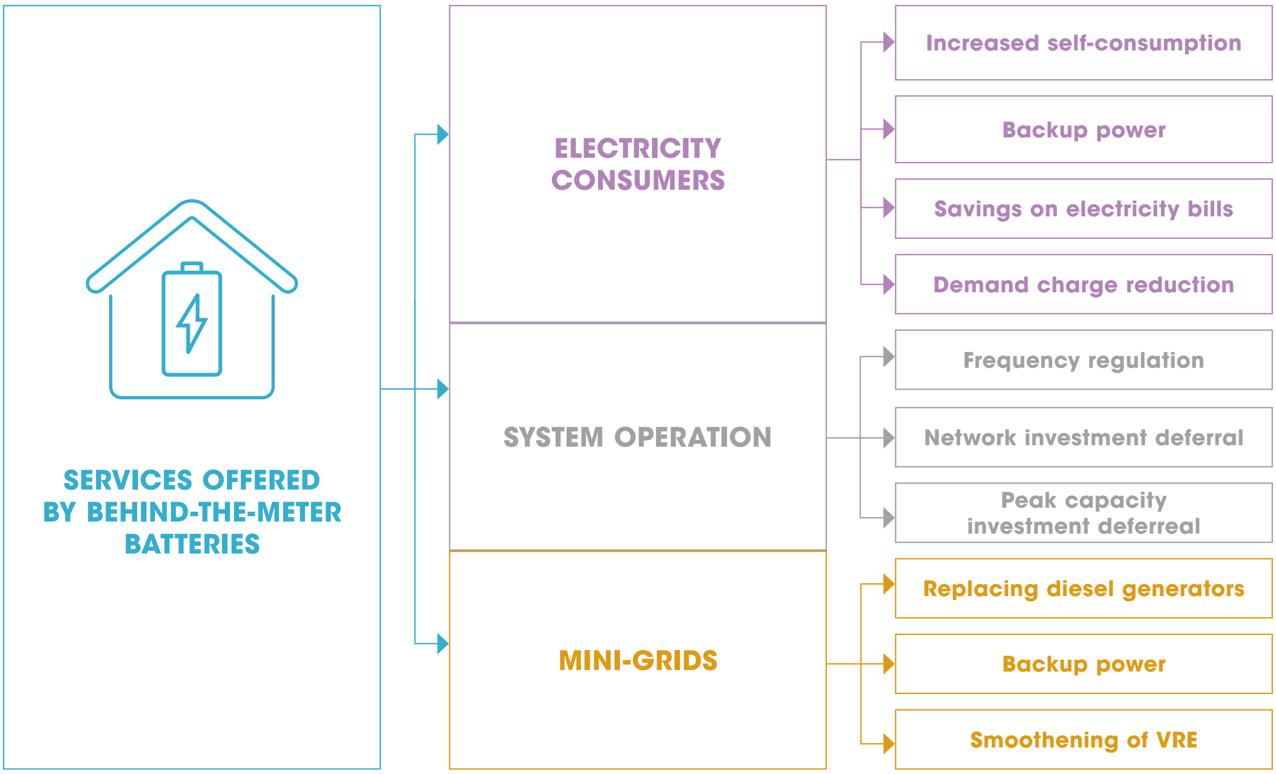
The share of VRE generation in the energy mix would need to grow from nearly 10% in 2019 to around 60% in 2050 (IRENA, 2019a) to be align with Paris Agreement. Almost half of PV deployment could be achieved in a distributed manner in the residential and commercial sectors, at both urban and rural sites (IRENA, 2019b).

II. CONTRIBUTION TO POWER SECTOR TRANSFORMATION

Behind-the-meter battery storage can enable the integration of VRE in the power system in various ways. Firstly, it supports the integration of local renewable energy generation by maximising self-consumption and its revenues. In jurisdictions where time-of-use electricity tariffs are in place, consumers can reduce their electricity bills by using the stored electricity when tariffs are high and maximising self-consumption from the solar rooftop when the battery is coupled with a solar PV system. This was, for example, the key driver of BTM battery deployment in Germany.

Secondly, BTM battery storage systems can provide voltage and frequency support, as well as other services, for system operators that help to integrate higher shares of VRE in the grid. In addition, batteries are an important tool to offset traditional grid investments in transmission, distribution and generation, by helping to reduce the peak load in the system. Finally, in renewable-based mini-grid systems, small-scale batteries play an important role in providing stability to the grid and replacing diesel generators. Figure 4 summarises the key services offered by BTM batteries.

Figure 4: Services provided by BTM battery storage systems



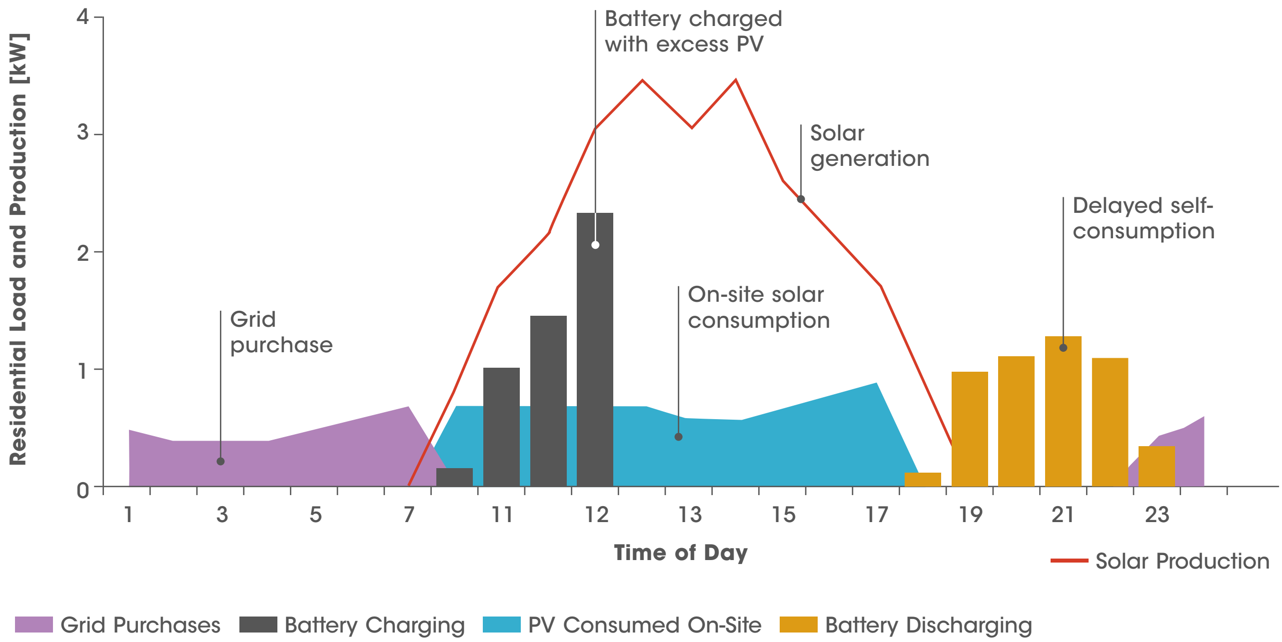
Services provided for electricity consumers

Increased self-consumption from distributed renewable generation

The excess electricity from distributed generation technologies, such as rooftop solar PV systems, can be stored in BTM batteries and used for local consumption when needed. In some geographies, where electricity injected into the grid is not remunerated, BTM battery storage would lead to increased self-consumption of the electricity produced by solar PV systems. In this way, BTM battery storage facilitates the deployment of distributed renewable energy technologies.

In places with high penetration of rooftop solar PV systems, distribution system operators could face challenges in absorbing increased variable generation from VRE sources. Therefore, maximising the local usage of such variable generation and minimising exports to the grid could benefit the system in some cases, and avoid issues related to the backflow of variable power. Figure 5 shows a typical solar PV generation curve, as well as the battery charging and discharging cycle increasing the hours of self-consumption.

Figure 5: Typical solar PV production and battery charging/discharging schedule



Source: Fitzgerald et al., 2015

Back-up power

BTM battery storage solutions can play a critical role in increasing the energy resiliency of consumers, by providing back-up power in case of grid outage. BTM battery storage can provide back-up power at various scales, ranging from sub-second-level power supply for important industrial operations, to 24-hour back-up by pairing with an on-site solar PV system.

For instance, Green Mountain Power (GMP), an electric utility in Vermont, the US, is piloting a project called “Resilient Home”. GMP is installing Tesla battery systems at the premises of its customers, who are able to use the batteries for back-up power. Interested customers pay USD 30 monthly for two batteries. This is significantly less expensive than the actual cost of the batteries and the installation, which reaches USD 7 000; however, in return, GMP is able to access the energy in the batteries to support its grid, like a virtual power plant (GMP, 2019; Lambert, 2018).

Savings on the electricity bill

Increased self-consumption by installing rooftop solar PV coupled with BTM battery systems can lead to significant electricity bill savings. When time-of-use tariffs are implemented, BTM battery storage systems allow consumers to reduce electricity costs by charging the batteries during off-peak hours, when tariffs are lower, and discharging them during peak time intervals, when tariffs are high.

Demand charge reduction

Demand charges are generally determined based on the highest electricity usage requirement (in terms of kW) for the consumer within a specified time period (usually ranging from 15 minutes to 3 months), depending on the utility. Demand charges can be significant for commercial and industrial consumers, especially during periods of peak demand. On-site battery storage systems can be used to manage peak loads and reduce demand charges.

For example, Poway Unified School District in the US state of California deployed a 6 MWh BTM battery storage system, provided by ENGIE Storage, across 12 campuses to curb steeply rising demand charges. This is expected to result in savings of approximately USD 1.4 million over 10 years (ENGIE Storage, 2018).

Services provided for system operators

Frequency regulation

BTM storage systems can provide frequency support to the grid by rapidly ramping its power output up or down, which helps smoothen the output of VRE generation. One precondition for these services is the ability of BTM storage to participate in the ancillary service market, usually through aggregators[1]. Alternatively, depending on the regulation, consumers can offer the availability of their battery to the operator in exchange for financial compensation. In this way, the operator can use the battery to balance the system at any time, thus providing the needed flexibility to integrate high shares of VRE. California already allows distributed energy resources, including rooftop solar, energy storage, PHEVs and demand response to participate in the wholesale electricity and ancillary service markets (CAISO, 2019).

In the Netherlands, Eneco Group, one of the largest Dutch utilities, started CrowdNett, a virtual power plant with a network of BTM batteries (Eneco, 2016). These batteries can be installed by homeowners and are used to improve self-consumption of solar energy as well as to provide grid services. Apart from increasing self-consumption and yielding bill savings to consumers, these batteries can participate in both electricity and ancillary service markets, yielding benefits to the grid as well. The battery owners receive financial compensation of up to EUR 500 per year for allowing the utilities to use their batteries for grid services. CrowdNett also has conducted pilots in Germany and Belgium (Eneco, 2018).

Network investment deferral

Distribution and transmission system operators invest in upgrading the system in order to meet anticipated demand growth. These upgrades are generally needed to meet the peak demand, which occurs for a small number of hours in the entire year. Even if the immediate anticipated demand growth is 1-3%, investments in network upgrades made by system operators can typically result in increasing the capacity of substations or lines by up to 25%, due to the standardised size of the equipment (RMI, 2015). This causes overinvestment vis-à-vis anticipated demand growth. BTM battery storage, together with the right incentives in place, can help consumers shift their demand so that it reduces the system’s peak demand, thus decreasing the need for grid reinforcements.

1 Aggregators are third parties that bundle distributed energy resources to engage as a single entity (also referred to as virtual power plants) in power or service markets; see the Innovation Landscape brief *Aggregators* (IRENA, 2019c).

Meeting peak demand through locally stored electricity reduces the need to draw power from the transmission system operators, thereby decreasing grid congestion and deferring network investments. Using distributed energy resources to avoid investment in the grid is also known as "virtual power lines". For example, UK Power Networks, a distribution network operator in the United Kingdom (UK), recently announced its plan to create London's first virtual power plant comprising solar panels and a fleet of batteries across 40 residences in the city. A trial concept was conducted in February 2018, wherein a fleet of 45 BTM batteries was used to meet peak demand. The project is expected to provide an alternative to the traditional approach of increasing network capacity to meet peak demand (UK Power Network, 2018).

In the US, the New York utility Con Edison is deploying a project to utilise BTM storage as part of an effort to defer a USD 1.2 billion substation. The initiative is part of Con Edison's Brooklyn-Queens Neighbourhood programme under New York's Reforming the Energy Vision initiative (Lalle, 2017).

Peak capacity investment deferral

To meet the peak demand in the power system, system operators need peak capacity resources. The utilisation level of such peak capacity is very low, however, and thus results in a high cost of power to consumers. For example, a study commissioned by the US state of Massachusetts estimated that the top 10% of the hours when electricity rates were the highest accounted for 40% of annual electricity spending (Customized Energy Solutions et al., 2016).

BTM storage systems can help defer investments in these expensive peak capacity resources in two ways. Firstly, they can reduce the peak demand itself by providing stored energy to consumers during peak times, thus reducing the need to procure energy from peak capacity resources. Secondly, BTM storage systems, through aggregators or retailers, can participate in capacity markets and compete with other participants to offer capacity. This can reduce the share of conventional generation-based capacity resources in the market while reducing prices in capacity markets. Further, since the peaking capacity requirement can vary from a very small amount to thousands of megawatts, aggregators of BTM storage systems can provide the right amount of storage capacity in exchange for capacity payments, thus avoiding investments in standard-sized peaking capacities.

For example, the utility Southern California Edison in the US selected a roster of energy storage projects to supply local capacity needs in the system, instead of the 262 MW natural gas peaker plant it had chosen previously. The utility is planning for a 100 MW/400 MWh system, complemented by a portfolio of smaller units, ranging from 10 MW to 40 MW. One developer, Swell, which aggregates fleets of home batteries, won a 14 MW contract for BTM demand response (Spector, 2019).

Services provided for mini-grids

BTM storage systems can replace diesel generators in renewable energy-based mini-grids. They can be used to provide back-up power when renewable generation is not available, as well as frequency and voltage to support the renewables' variability. BTM batteries can smoothen variable generation and shift the generation curve of small solar PV and wind systems connected at the consumer end to meet peak demand.

For example, Electro Power Systems, a French storage developer and system integrator, has expanded a microgrid with 1.8 MWh of battery storage along with a 1.75 MW solar PV solution in Somalia. The microgrid serves more than 50 000 people and helps the local region meet 90% of its electricity demand from renewables and battery storage (Colthorpe, 2017a).

Potential impact on power sector transformation

The increasing adoption of BTM battery storage systems can help consumers greatly reduce their electricity costs. It will further help to stabilise the grid and to effectively absorb variable power from renewable energy sources.

- Poway Unified School District in California installed a 6 MWh BTM storage system. The expected **savings of this project are around USD 1.4 million over 10 years**, and the main application is demand charge reduction (ENGIE Storage, 2018).

- Green Mountain Power plans to install 2 000 Tesla Powerwall 2 units at its customers' premises in Vermont (US) to provide **back-up power** and support the grid. The utility expects consumers to incur **between USD 2 million and USD 3 million** in savings across the programme's lifetime. With regard to grid benefits, the batteries installed, via peak shaving, helped cover Vermont's peak demand in July 2018 and **saved the utility USD 500 000** (Brooks, 2018).

- Advanced Microgrid Solutions (AMS) completed a battery-based storage project for Morgan Stanley in the US, which resulted in a **20% peak demand reduction**, using 500 kW / 1 000 kWh Tesla Powerpack batteries. Peak demand charges for commercial and industrial consumers in the US can constitute up to 50% of their bill. This system is integrated into the existing building management system (Colthorpe, 2017b).

- Stem, an energy storage company, has provided a BTM battery storage fleet of 1 MW capacity situated across 29 customer sites in Oahu, Hawaii to help the Hawaiian Electric Company **integrate more renewable energy** in the Oahu grid. Testing has confirmed that the fleet is able to manage different load shapes and characteristics to serve the utility (Stem, Inc., 2017a).

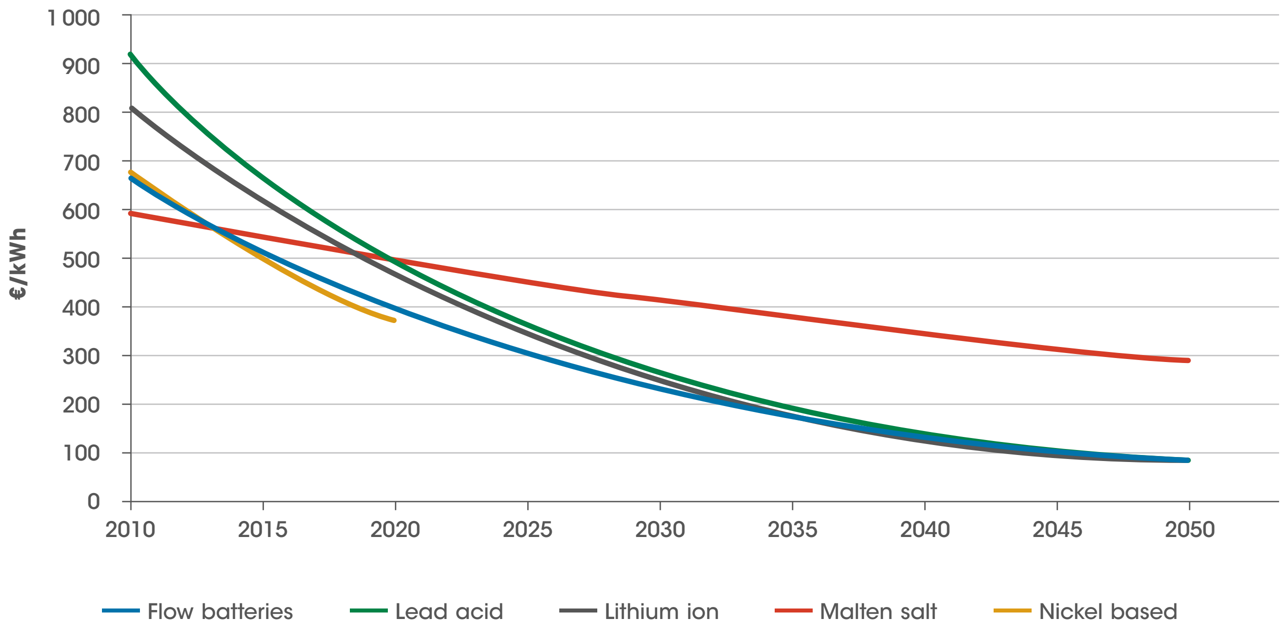
III. KEY FACTORS TO ENABLE DEPLOYMENT

Although the BTM battery storage market is growing at a rapid pace, its further growth can be accelerated by overcoming the existing challenges related to high upfront costs. These challenges should be addressed through various government and private sector initiatives, incentive schemes, robust regulatory frameworks and knowledge dissemination among various stakeholders.

Reducing upfront costs

A further reduction in the upfront costs of BTM batteries would be the key enabler for this market to grow. Figure 6 provides an illustration of pricing trends and forecasts for BTM energy storage technologies. This represents an average of costs across all types of consumer markets and assumes systems with a two-hour discharge duration (for example, 5 kW/10 kWh).

Figure 6: Battery system cost trends in EUR/kWh



Source: Ecofys et al., 2016

The costs of BTM storage systems have declined considerably in the past few years. Although system costs are expected to continue to fall, the growth of this market depends on the tariff structures and incentives that are available for BTM customers and on the proactivity of local retailers and system operators.

Active interventions by state/federal governments – such as upfront subsidies/rebates or funding of pilots – can be important catalysts to promote BTM storage systems, especially before the industry gains economies of scale and overcomes the high initial soft costs.

The California Public Utilities Commission in the US has established a Self-Generation Incentive Program (SGIP) to help reduce the initial costs of storage for consumers. SGIP provides rebates for qualifying distributed energy systems installed on the customer's side of the utility meter. The incentive rate declines over time as the market matures. On a state-wide basis, approximately USD 330 million has been allocated for storage projects above 10 kW and around USD 48 million has been allocated for storage projects below 10 kW (CPUC, 2019).

Similarly, the Swedish government has a subsidy scheme to cover 60% of the upfront cost of a residential storage system up to a maximum of USD 5 400. Battery, wiring, management systems and installation will all be eligible for payment under the subsidy. The subsidy is part of Sweden's plan to boost PV utilisation and to establish a smarter, more flexible grid (Hanley, 2016).

Enabling regulatory framework: Time-of-use tariffs and net billing

An important enabler for BTM batteries is a regulatory framework in the retail market that seeks to maximise benefits for consumers, while incentives demand-side flexibility. Time-of-use tariffs, for example, are demand response enablers, allowing consumers to adjust their electricity consumption (including the use of BTM storage) to reduce their electricity bills. Time-of-use tariffs allow consumers to observe the periods of low and high electricity prices and thereupon decide when to charge the battery (see the Innovation Landscape brief *Time-of-use tariffs* [IRENA, 2019d]).

BTM batteries could also benefit from net billing schemes, mainly when batteries are coupled with generation technologies. Net billing compensation is based on the value of the kWh consumed or injected in the grid. It incentivises prosumers to provide stored energy to the grid when remuneration is high and to store the generated electricity during low-demand time intervals (see the Innovation Landscape brief *Net billing schemes* [IRENA, 2019e]).

Reducing soft costs such as interconnection and permitting

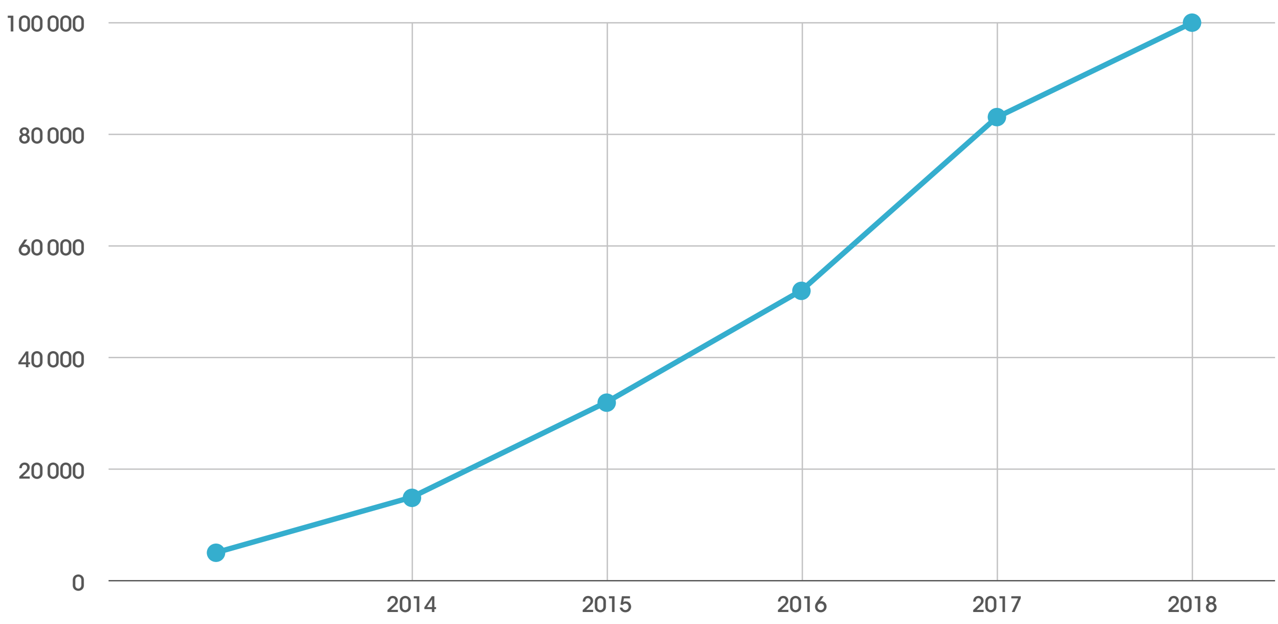
"Soft costs" such as interconnection, permitting and development costs can account for a significant share of the installed cost of BTM storage systems, particularly where the industry has not yet gained scale. Regulators should consider reducing the process time for interconnection and permitting, which results in notably higher all-in costs for storage developers and customers.

IV. CURRENT CONTEXT AND EXAMPLES OF ONGOING INITIATIVES

Growth in BTM battery storage is being driven by residential, commercial and industrial consumers that can deploy these systems at scale and harness significant savings in their energy bills. This trend is expected to accelerate as costs of energy storage are expected to decline further, making storage even more viable for consumers. Australia, China, Germany, Italy, Japan, the Netherlands, the UK and the US are examples of countries where BTM batteries are being deployed.

In Germany, around 100 000 commercial and residential solar PV with BTM storage systems had been implemented by summer 2018 (Rathi, 2018). This number is expected to double by 2020 (Parkin, 2018).

Figure 7: Household battery storage systems in Germany from 2013 to 2018



Source: Rathi, 2018

Several companies that are using BTM storage systems across various geographies are described below.

sonnenCommunity (Germany)

The sonnenCommunity is an aggregator in Germany consisting of around 10 000 customers with battery storage, solar PV generation or both. Launched in 2015, the sonnenCommunity was used mostly for peer-to-peer trading within the virtual power plant. In 2017, the virtual power plant became available to the power grid to provide frequency regulation. Compared to other alternatives, such as pumped hydropower storage, this distributed "virtual" storage resource can react very quickly (sub-second), making it a great provider of primary frequency services (sonnenCommunity, 2018). Typically members of sonnenCommunity can cover 80% of their electricity needs by utilising power from their solar and/or battery systems. The remaining electricity may have to be purchased from the grid (St. John, 2016).

In 2016, measures to manage grid congestion cost Germany around EUR 800 million, a large part of which was for wind curtailment (Grey Cells Energy, 2018). Re-dispatch measures are necessary in the country, where the wind energy produced in the north cannot be transported to the industrial centres located in the south. In response, in 2017 sonnen partnered with the German grid operator TenneT to launch the pilot project sonnen eServices. This project integrated batteries into the power system via a blockchain solution (developed by IBM). In this pilot project, a network of residential solar batteries was made available to help reduce the limitations imposed on wind energy at times of insufficient transport capacity.

Advanced Microgrid Solutions (United States)

Advanced Microgrid Solutions (AMS) uses different storage technologies and a data analytics software programme to provide commercial and industrial consumers with battery storage systems to optimise their energy usage. It also allows the fleet of battery storage systems to provide grid services to the system operators. The data analytics software uses multiple data points, such as consumption as well as retail and wholesale energy prices, in addition to energy efficiency metrics, to develop a customised energy profile for each customer. The software then optimises the energy usage in real time, at the building and fleet levels, to reduce costs.

AMS is operating the world's biggest virtual power plant, in the form of a 27 MW/142 MWh fleet of batteries located at commercial and industrial sites across the territory of the utility Southern California Edison. The fleet delivered more than 2 gigawatt-hours of battery power for the utility in one year (St. John, 2019).

Also, AMS managed to reduce the peak demand by 20% for Morgan Stanley, using 500 kW/1 000 kWh Tesla Powerpack batteries. At California State University, AMS has implemented a 2 MW/12 MWh storage system, spread across three sites, which has resulted in peak energy cost savings of USD 3.3 million.

Stem (United States)

Stem, a US energy services provider, helps commercial and industrial customers reduce their energy bills by using energy stored in their batteries during periods of peak demand. The company combines the battery storage with a cloud-based analytics system to identify the best time to draw energy from the battery storage (Colthorpe, 2017c). It also utilises a fleet of deployed customer-sited storage systems to provide grid services to system operators.

In 2014, Stem won a contract with Southern California Edison to provide 85 MW of local capacity by 2021 (St. John, 2019). Stem also has provided emergency grid relief in California by utilising its fleet of BTM battery storage devices. In June 2017, when an unprecedented heat wave struck the state, wholesale electric prices started rising. Stem dispatched 1.6 MW of stored energy from its fleet of storage systems within one hour to seven critical areas of the grid to provide demand response services (Stem, Inc., 2017b).

Stem also operates the 162 kW/180 kWh battery storage system installed at offices in San Francisco. The intended application for the system is to provide demand charge management for Adobe along with demand response services to the California Independent System Operator. The project is expected to result in cost savings of approximately USD 255 600 over a 10-year period (Stem, Inc., n.d.).

Other examples of BTM battery projects

Table 1 List of some projects using BTM batteries

Project name	Location	Service provided	Description
Johnson Control International's 100 kW/ 182 kWh BTM energy storage system at its APAC headquarters	Shanghai, China	**Demand charge reduction** **Increased self-consumption**	The intended application of the BTM battery is to reduce utility costs through demand charge management along with providing storage for the installed solar PV system and providing charging the EVs (Johnson Controls, n.d.).
Case Western Reserve University's 125 kW/ 65 kWh lithium-ion BTM storage system	Ohio, US	**Backup power** **Frequency regulation** **Renewable energy smoothening**	The system has been integrated with an existing wind power plant and may be integrated with a solar plant. The intended application is to smoothen the output from the wind plant, to provide back-up power to university and to provide frequency regulation services to the grid (Johnson Controls, n.d.).
Clemson University's 50 kW/160 kWh BTM battery storage system	Wisconsin, US	**Electricity bill savings**	The intended application for this system is to shift demand of the building to off-peak hours, thus generating saving on electricity bills based on time-of-use tariffs (Johnson Controls, 2017).

V. IMPLEMENTATION REQUIREMENTS: CHECKLIST

TECHNICAL REQUIREMENTS

Hardware:

- Deployment of BTM batteries
- Metering equipment, such as smart meters or devices built into the storage systems (required to provide real-time power consumption and production information)
- Smart meters

Software:

- Aggregation software with algorithms calculating the optimal operation of each unit
- Real-time communication between the aggregator and the hardware system
- Distribution system management software ensuring reliability and safe operations

POLICIES NEEDED

Policies should be aimed at:

- Appropriately valuing and capturing the unique set of benefits that energy storage systems can provide (*e.g.*, valuation through demand-side management studies, and capturing of value through wholesale market or demand-side management programme participation)
- Simple and fast interconnection and permitting processes
- Low-cost funding programmes to reduce upfront cost burdens of installing the battery.

REGULATORY REQUIREMENTS

Retail market:

- Time-of-use tariffs and net billing schemes to incentivise demand response programmes and therefore maximise the benefits of BTM storage for consumers
- Provisions for allowing distributed energy resources, including BTM energy storage assets to provide grid services
- Definition of technical and operational standards
- Establishment of clear, fair and non-discriminatory valuation and remuneration frameworks
- Establishment of fair and non-discriminatory charges

Distribution and transmission system:

- Allowing transmission and distribution system operators to procure market-based flexibility services from distributed energy resources, including BTM batteries
- Establishment of local markets for distribution system operators to procure services to avoid grid congestion and ensure reliability
- Increased co-ordination between distribution and transmission system operators

Wholesale market:

- Allow participation of aggregators and/or distributed energy resources in electricity wholesale markets and ancillary service markets
- Allowing decentralised resources to provide services to central/local grids
- Clear price signals to guide aggregators and BTM batteries operations

STAKEHOLDER ROLES AND RESPONSIBILITIES

Regulators:

- Defining the vision for BTM storage systems deployment – the BTM implementation roadmap, planning and optimising the location of BTM storage systems

Aggregators:

- Provide grid-related services to distribution and transmission system operators, if the market is established
- Information exchange with distribution system operators related to capacity, location and type of distributed energy resources

ACRONYMS AND ABBREVIATIONS

AMS	Advanced Microgrid Solutions
BTM	behind-the-meter
EUR	Euro
EV	electric vehicle
FTM	front-of-the-meter
GMP	Green Mountain Power
PHEV	plug-in hybrid electric vehicle
PV	photovoltaic
SGIP	Self-Generation Incentive Program
UK	United Kingdom
US	United States
USD	US dollar
VRE	variable renewable energyy

UNITS OF MEASUREMENT

kW	kilowatt
kWh	kilowatt-hour
MW	megawatt
MWh	megawatt-hour

BIBLIOGRAPHY

Advanced Microgrid Solutions (2018), “Projects”, http://advmicrogrid.com/projects.html.

Brooks, D. (2018), “Using customer batteries as a power source saved Vt. utility $500K”, Granite Geek, https://granitegeek.concordmonitor.com/2018/07/23/using-customer-batteries-as-a-power-source-saved-vt-utility-500k/.

CAISO (2019), “Energy storage and distributed energy resources”, California Independent System Operator, http://www.caiso.com/informed/Pages/StakeholderProcesses/EnergyStorage_DistributedEnergyResources.aspx.

Colthorpe, A. (2017a), “EPS’ Somali microgrid upgrade which helps city hit 90% renewables completed in less than 30 days”, Energy Storage News, https://www.energy-storage.news/news/eps-somali-microgrid-upgrade-which-helps-city-hit-90-renewables-completed-i.

Colthorpe, A. (2017b), “AMS to develop 40MWh of ‘Hybrid Electric Buildings’ for Walmart”, Energy Storage News, https://www.energy-storage.news/news/ams-to-develop-40mwh-of-hybrid-electric-buildings-for-walmart.

Colthorpe, A. (2017c), “Stem connects 1MW aggregated virtual power plant in Hawaii”, Energy Storage News, https://www.energy-storage.news/news/stem-connects-1mw-aggregated-virtual-power-plant-in-hawaii.

CPUC (2019), “Self-Generation Incentive Program”, California Public Utilities Commission, http://www.cpuc.ca.gov/sgip/.

Customized Energy Solutions, Alevo Analytics, Sustainable Energy Advantage LLC and Daymark Energy Advisors (2016), *State of charge*, Massachusetts Energy Storage Initiative.

Ecofys, VITO, Technopolis, Fraunhofer IWES and Strategen (2016), *Battery-based energy storage roadmap*, Batstorm Project, http://www.batstorm-project.eu/sites/default/files/BATSTORM_1st_roadmap_workshop_report.pdf.

Eneco (2018), “That’s how CrowdNett works”, https://www.eneco.nl/crowdnett/hoe-werkt-crowdnett/.

Eneco (2016), "Network of home batteries forms sustainable backup for national power grid", https://news.enecogroup.com/network-of-home-batteries-forms-sustainable-backup-for-national-power-grid/.

ENGIE Storage (2018), "Poway Unified School District", http://go.engiestorage.com/acton/attachment/34864/f-001e/1/-/-/-/-/Poway%20USD%20ES%20CS.pdf.

ESA (2018), "A beginner's Guide to Energy Storage", Energy Storage Association, http://energystorage.org/system/files/resources/slides_completev2.pdf.

Fitzgerald, G., J. Mandel and J. Morris (2015), *The economics of battery energy storage: How multi-use, customer-sited batteries deliver the most services and value to customers and the grid,* Rocky Mountain Institute, Basalt, Colorado, US.

GMP (2019), "Resilient Home",Green Mountain Power, https://greenmountainpower.com/product/powerwall/.

Grey Cells Energy (2018), "Sonnen's 'Community': Aggregating domestic battery storage", https://greycellsenergy.com/examples/sonnens-community-aggregating-domestic-battery-storage/.

Hanley, S. (2016), "Sweden will offer 60% subsidy for residential battery storage costs", CleanTechnica, https://cleantechnica.com/2016/11/22/sweden-will-offer-60-subsidy-residential-battery-storage-costs/.

IRENA (2019a), *Innovation landscape for a renewable-powered future: Solutions to integrate variable renewables*, International Renewable Energy Agency, Abu Dhabi, https://www.irena.org/publications/2019/Feb/Innovation-landscape-for-a-renewable-powered-future.

IRENA (2019b), *Global energy transformation: A roadmap to 2050*, International Renewable Energy Agency, Abu Dhabi, https://www.irena.org/publications/2019/Apr/Global-energy-transformation-A-roadmap-to-2050-2019Edition.

IRENA (2019c), the Innovation Landscape brief *Aggregators*, International Renewable Energy Agency, Abu Dhabi, https://www.irena.org/-/media/Files/IRENA/Agency/Publication/2019/Feb/IRENA_Innovation_Aggregators_2019.PDF?la=en&hash=EB86C1C86A7649B25050F57799F2C0F609894A01.

IRENA (2019d), the Innovation Landscape brief *Time-of-use tariffs,* International Renewable Energy Agency, Abu Dhabi, https://www.irena.org/-/media/Files/IRENA/Agency/Publication/2019/Feb/IRENA_Innovation_ToU_tariffs_2019.pdf?la=en&hash=36658ADA8AA98677888DB2C184D1EE6A048C7470.

IRENA (2019e), the Innovation Landscape brief *Net billing schemes,* International Renewable Energy Agency, Abu Dhabi, https://www.irena.org/-/media/Files/IRENA/Agency/Publication/2019/Feb/IRENA_Net_billing_2019.pdf?la=en&hash=DD239111CB0649A9A9018BAE77B9AC06B9EA0D25.

IRENA (2017), *Electricity storage and renewables: Costs and markets to 2030,* International Renewable Energy Agency, Abu Dhabi, https://www.irena.org/-/media/Files/IRENA/Agency/Publication/2017/Oct/IRENA_Electricity_Storage_Costs_2017.pdf.

Johnson Controls (2017), "Johnson Controls teams with Clemson University to adopt technology for a new building that runs smartly and efficiently while saving on energy costs", International Renewable Energy Agency, Abu Dhabi, http://www.johnsoncontrols.com/media-center/news/press-releases/2017/06/28/johnson-controls-teams-with-clemson-university-to-adopt-technology-for-a-new-building-that-runs-smartly-and-efficiently-while-saving-on-energy-costs.

Johnson Controls (n.d.), "Distributed energy storage news and resources", http://www.johnsoncontrols.com/distributed-energy-storage/news-and-resources.

Lalle, A. (2017), "Con Edison projects explore the potential of energy storage", T&D World, http://www.tdworld.com/distribution/con-edison-projects-explore-potential-energy-storage.

Lambert, F. (2018), "Tesla and GMP are installing up to 2,000 Powerwalls in Vermont, only ~10% installed", Electrek, https://electrek.co/2018/04/06/tesla-powerwall-delivered-massive-batch/.

Lazard (2018), *Lazard's Levelized Cost of Storage Analysis – Version 4.0,* Lazard, https://www.lazard.com/media/450774/lazards-levelized-cost-of-storage-version-40-vfinal.pdf.

Martin, J. (2018), "Household battery storage incentive schemes: What's available and where", One Step Off The Grid, https://onestepoffthegrid.com.au/battery-incentive-programs-around-australia-existing-proposed/.

Parkin, B. (2018), Germany Kicking Off Home Solar Battery Boom as Prices Drop

Rathi, A. (2018), "100,000 homes in Germany now have battery-storage systems connected to the grid", Quartz, https://qz.com/1372939/100000-homes-in-germany-now-have-battery-storage-systems-connected-to-the-grid/.

RMI (2015), *The economics of battery energy storage,* Rocky Mountain Institute, Basalt, Colorado, US.

sonnenCommunity (2018), https://sonnenbatterie.de/en/sonnenCommunity.

Spector, J. (2019), "Southern California Edison picks 195MW battery portfolio in place of Puente Gas Plant", Greentech Media, https://www.greentechmedia.com/articles/read/sce-picks-major-battery-portfolio-in-place-of-puente-gas-plant.

St. John, J. (2019), "AMS breaks 2 gigawatt-hours in grid services", Greentech Media, https://www.greentechmedia.com/articles/read/advanced-microgrid-solutions-breaks-2-gigawatt-hours-in-grid-services.

St. John, J. (2016), "Sonnen raises $85M to scale its behind-the-meter battery business", Greentech Media, https://www.greentechmedia.com/articles/read/sonnen-raises-85m-to-scale-its-behind-the-meter-battery-business.

Stem, Inc. (2017a), "Stem connects one megawatt of energy storage for Hawaiian Electric", http://www.stem.com/stem-connects-one-megawatt-of-energy-storage-for-hawaiian-electric/.

Stem, Inc. (2017b), "Stem energy storage network delivers emergency grid relief in California heat", http://www.stem.com/stem-energy-storage-network-delivers-emergency-grid-relief-in-california-heat/.

Stem, Inc. (2015), "Stem reduced Alsco's electricity spend by more than $10,000 in first year", http://3zkqyz2t3xwi492ll518psvq.wpengine.netdna-cdn.com/wp-content/uploads/2017/01/stem-alsco-case-study-FIN.pdf.

Stem, Inc. (n.d.), "Case studies", http://www.stem.com/case-studies/.

UK Power Networks (2018), "Electricity network plan to launch London's first 'virtual power station'", News&press, www.ukpowernetworks.co.uk/internet/en/news-and-press/first-virtual-power-station.html.

IRENA
International Renewable Energy Agency

BEHIND-THE-METER BATTERIES
INNOVATION LANDSCAPE BRIEF

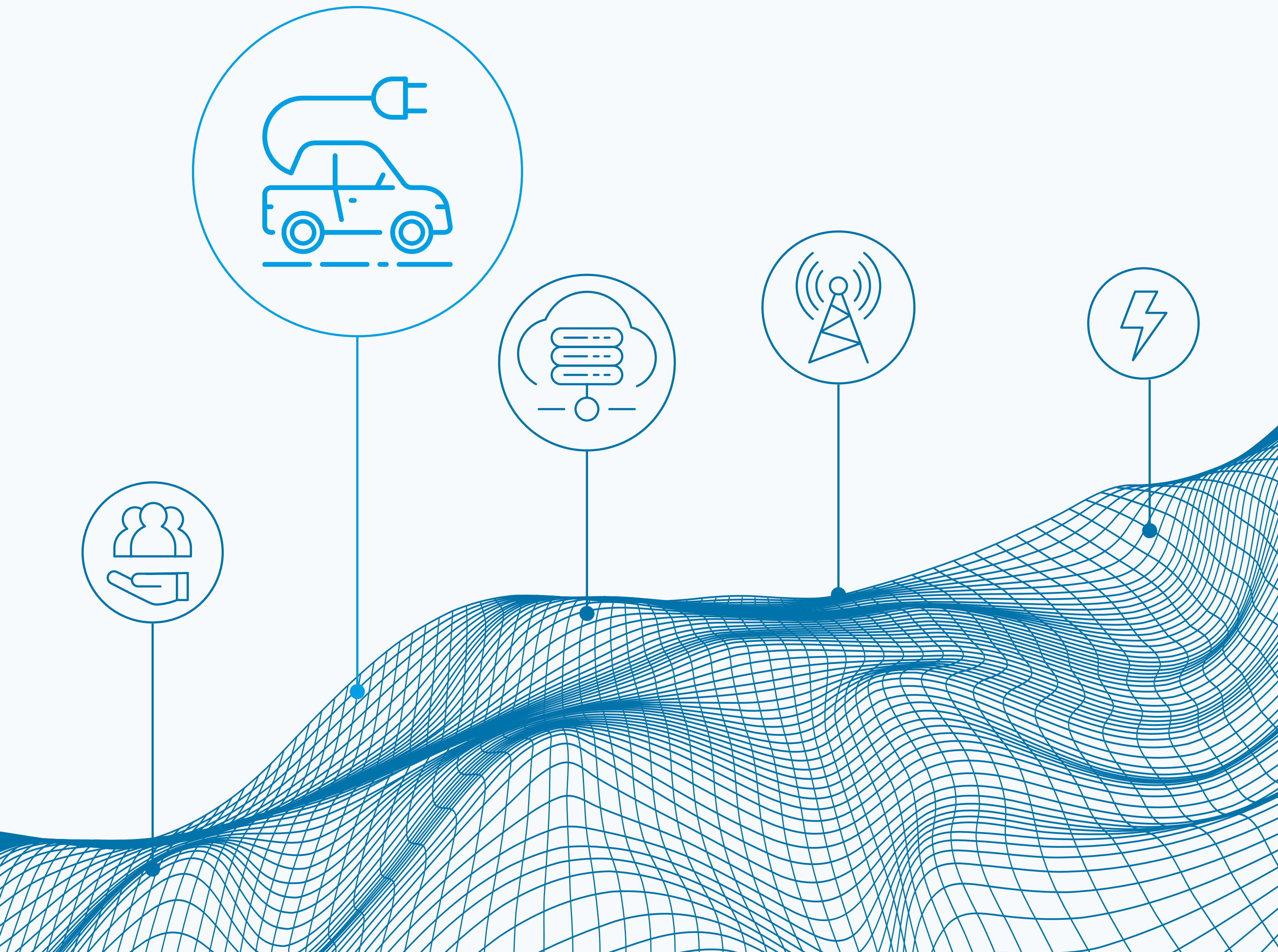
IRENA HEADQUARTERS
P.O. Box 236, Abu Dhabi
United Arab Emirates

www.irena.org

IRENA
International Renewable Energy Agency

ELECTRIC-VEHICLE SMART CHARGING

INNOVATION LANDSCAPE BRIEF



ISBN 978-92-9260-141-6

Citation: IRENA (2019), *Innovation landscape brief: Electric-vehicle smart charging,* International Renewable Energy Agency, Abu Dhabi.

ACKNOWLEDGEMENTS

This report was prepared by the Innovation team at IRENA's Innovation and Technology Centre (IITC) with text authored by Arina Anisie, Francisco Boshell and Javier Sesma.

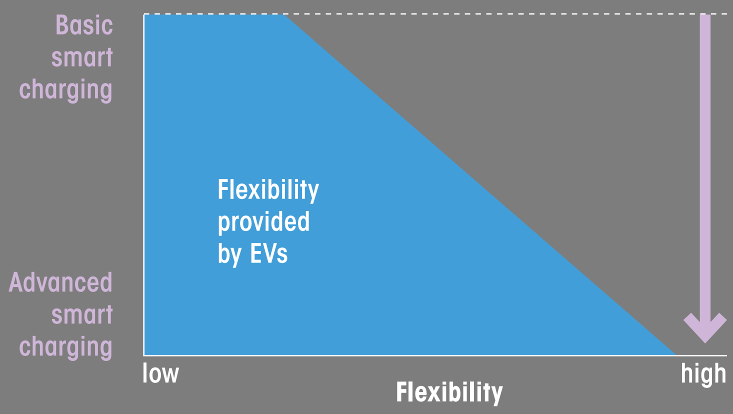
Valuable external review was provided by Ulf Schulte, Mereille Klein Koerkamp-Schreurs and Stephan Hell (Allego), Carlo Mol (VITO), Kalle Petteri Rauma (TU Dortmund), Carlos Pueyo (CIRCE) and Stefan Nykamp (Innogy SE), along with Martina Lyons, Nina Litman-Roventa and Paul Komor (IRENA).

Report available online: www.irena.org/publications
For questions or to provide feedback: publications@irena.org

1 BENEFITS

Smart charging of EVs enables:

- Reduce grid infrastructure investments
- Network congestion management
- Peak shaving
- Provision of ancillary services



2 KEY ENABLING FACTORS

- Charging infrastructure development and deployment
- ICT control and communication protocols
- Define roles and responsibilities of stakeholders
- Design regulation for vehicle-grid integration
- Big data and artificial intelligence for smart charging

3 SNAPSHOT

- → 5.6 million EVs on the world's roads as of the beginning of 2019
- → 5.2 million EV chargers in 2018 (540 000 publicly available)
- → Smart charging of EVs can significantly reduce the peak load and avoid grid reinforcements, at a cost of 10% of the total cost of reinforcing the grid

WHAT IS SMART CHARGING?

Smart charging means adapting the charging cycle of EVs to both the conditions of the power system and the needs of vehicle users. This facilitates the integration of EVs while meeting mobility needs.

ELECTRIC-VEHICLE SMART CHARGING

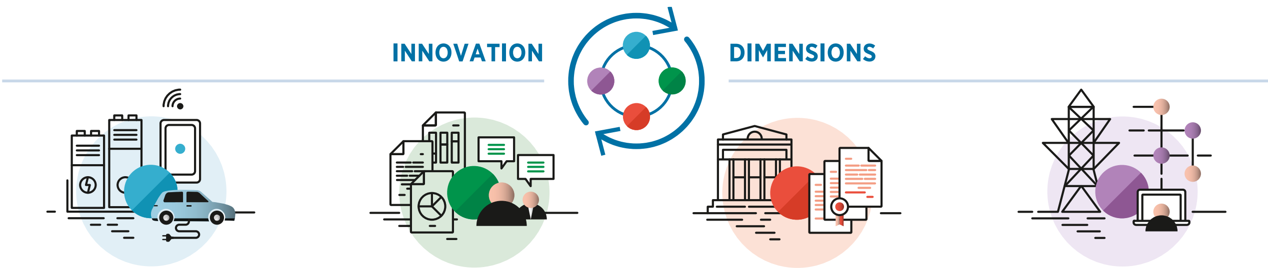
Smart charging for electric vehicles (EVs) holds the key to unleash **synergies between clean transport** sector and **low-carbon electricity.** It minimises the load impact from EVs and unlocks the flexibility to use more **solar and wind power.**

ABOUT THIS BRIEF

This brief is part of the IRENA project "Innovation landscape for a renewable-powered future", which maps the relevant innovations, identifies the synergies and formulates solutions for integrating high shares of variable renewable energy (VRE) into power systems.

The synthesis report, *Innovation landscape for a renewable-powered future: Solutions to integrate variable renewables* (IRENA, 2019a), illustrates the need for synergies between different innovations to create actual solutions. Solutions to drive the uptake of solar and wind power span four broad dimensions of innovation: enabling technologies, business models, market design and system operation.

Along with the synthesis report, the project includes a series of innovation landscape briefs, each covering one of 30 key innovations identified across those four dimensions. The 30 innovations are listed in the figure below.



ENABLING TECHNOLOGIES

1 Utility scale batteries
2 Behind-the-meter batteries

3 Electric-vehicle smart charging
4 Renewable power-to-heat
5 Renewable power-to-hydrogen

6 Internet of Things
7 Artificial intelligence and big data
8 Blockchain

9 Renewable mini-grids
10 Supergrids

11 Flexibility in conventional power plants

BUSINESS MODELS

12 Aggregators
13 Peer-to-peer electricity trading
14 Energy-as-a-service

15 Community-ownership models
16 Pay-as-you-go models

MARKET DESIGN

17 Increasing time granularity in electricity markets
18 Increasing space granularity in electricity markets
19 Innovative ancillary services
20 Re-designing capacity markets
21 Regional markets

22 Time-of-use tariffs
23 Market integration of distributed energy resources
24 Net billing schemes

SYSTEM OPERATION

25 Future role of distribution system operators
26 Co-operation between transmission and distribution system operators

27 Advanced forecasting of variable renewable power generation
28 Innovative operation of pumped hydropower storage

29 Virtual power lines
30 Dynamic line rating

This brief provides an overview of the services that electric vehicles (EVs) can provide to the power system through smart charging, and of the importance of such charging schemes for the smooth integration of EVs in the grid. This brief looks into unidirectional (V1G) and bidirectional vehicle-to-grid (V2G) technologies and on their role in integrating higher renewable energy shares, while providing services to the grid.

For a more in-depth study of all these aspects, together with business models and regulatory framework analysis, projections of the flexibility provided by EVs to the system and the possible impact of the expected mobility disruptions, please read IRENA's report *'Innovation outlook: Smart charging for electric vehicles'* (IRENA, 2019c).

The brief is structured as follows:

I Description

II Contribution to power sector transformation

III Key factors to enable deployment

IV Current status and examples of ongoing initiatives

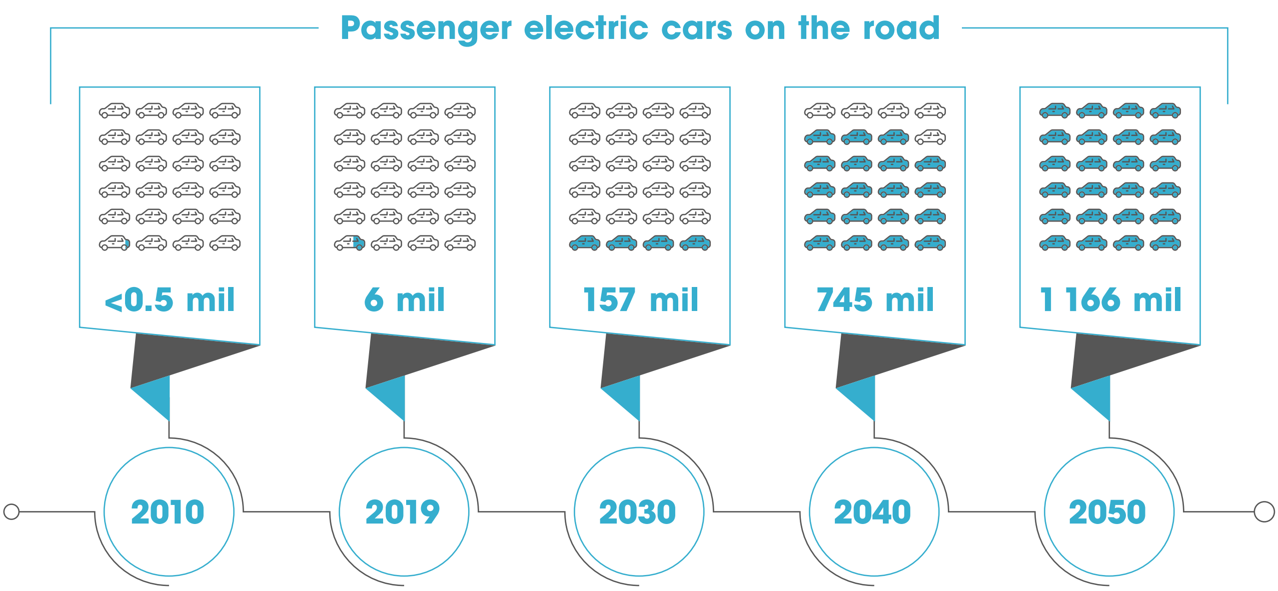
V Implementation requirements: Checklist

I. DESCRIPTION

EVs represent a paradigm shift for both the transport and power sectors, with the potential to advance the decarbonisation of both sectors by coupling them. Although the transport sector currently has a very low share of renewable energy, it is undergoing a fundamental change, particularly in the passenger road vehicle segment where EVs are emerging.

According to Germany's Centre for Solar Energy and Hydrogen Research (ZSW), 5.6 million EVs were on the world's roads as of the beginning of 2019. China and the United States were the largest markets, with 2.6 million and 1.1 million EVs, respectively. If most of the passenger vehicles sold from 2040 onwards were electric, more than 1 billion EVs could be on the road by 2050 (see Figure 1). IRENA analysis indicates that future EV battery capacity may dwarf stationary battery capacity. In 2050, around 14 terawatt-hours (TWh) of EV batteries would be available to provide grid services, compared to 9 TWh of stationary batteries (IRENA, 2019b).

Figure 1: Growth in EV deployment between 2010 and 2050 in Paris Agreement-aligned scenario



Source: IRENA, 2019b

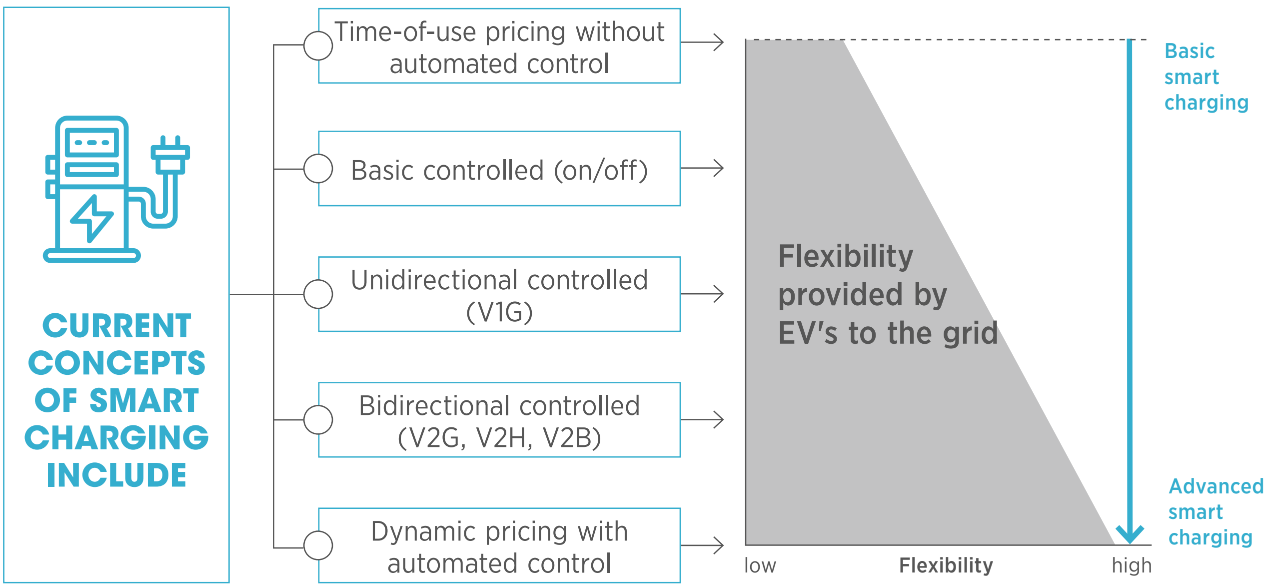
The cost reductions in renewable power generation make electricity an attractive low-cost fuel for the transport sector in many countries. A significant scaling up in EV deployment represents an opportunity for the power sector as well. EV fleets can create vast electricity storage capacity. They can act as flexible loads and as decentralised storage resources, capable of providing additional flexibility to support power system operations. With smart charging, EVs could adapt their charging patterns to flatten peak demand, fill load valleys and support real-time balancing of the grids by adjusting their charging levels. The use of EVs as a flexibility resource via smart charging approaches would reduce the need for investment in flexible, but carbon-intensive, fossil fuel power plants to balance renewables.

Smart charging means adapting the charging cycle of EVs to both the conditions of the power system and the needs of vehicle users. This facilitates the integration of EVs while meeting mobility needs (IRENA, 2019c). Smart charging therefore is a way of optimising the charging process according to distribution grid constraints, the availability of local renewable energy sources and customers' preferences.

Smart charging allows a certain level of control over the charging process. It includes different pricing and technical charging options. The simplest form of incentive – time-of-use pricing – encourages consumers to move their charging from peak to off-peak periods. More advanced smart charging approaches, such as direct control mechanisms, will be necessary as a long-term solution at higher penetration levels and for the delivery of close-to-real-time balancing and ancillary services, as illustrated in Figure 2.

Such mechanisms range from simply switching on and off the charging, to unidirectional control of vehicles (V1G) that allows for increasing or decreasing the rate of charging, to the technically challenging bidirectional vehicle-to-grid (V2G), which allows the EV to provide services to the grid in the discharge mode. In addition, vehicle-to-home (V2H) and vehicle-to-building (V2B) are forms of bidirectional charging where EVs are used as a residential back-up power supply during periods of power outage or for increasing self-consumption of energy produced on-site (demand charge avoidance).

Figure 2: Smart charging enables EVs to provide flexibility



Source: IRENA, 2019c

II. CONTRIBUTION TO POWER SECTOR TRANSFORMATION

Reduced investments in grid infrastructure

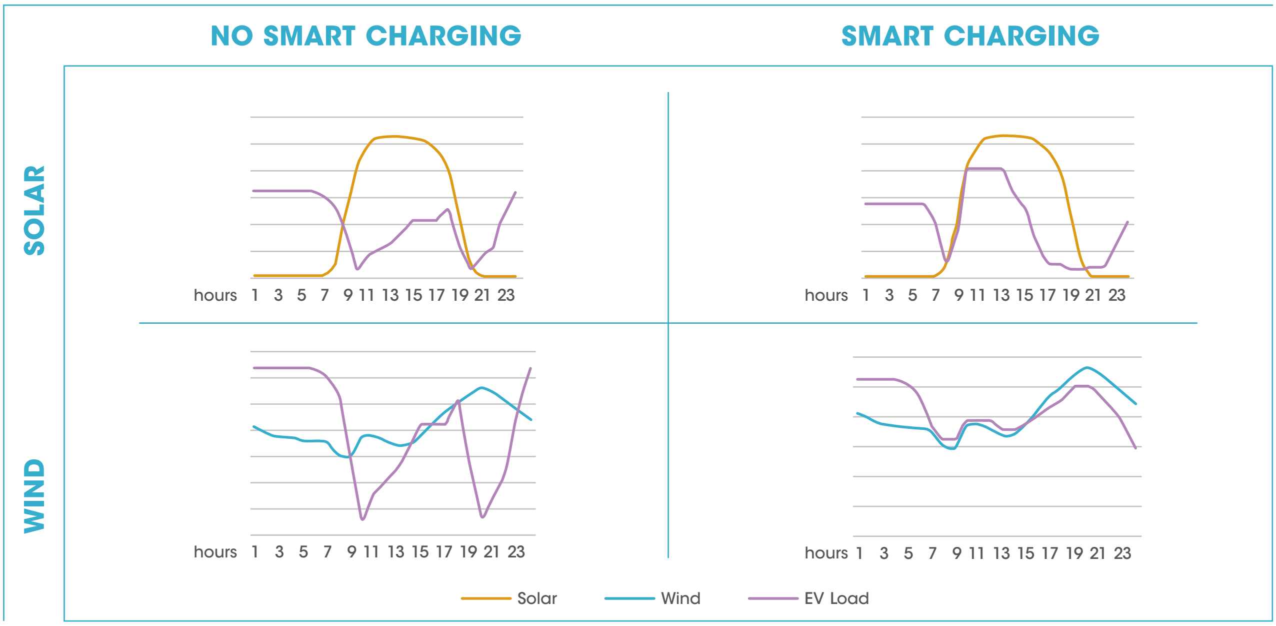
If EVs were charged in an uncontrolled way, they could increase the peak on the grid since charging trends could match existing load peaks and thus contribute to overloading and the need for upgrades at the distribution and transmission levels. Additionally, this extra load would result in upgrade needs in the generation capacity. However, the uptake of smart charging for electric mobility is expected to establish a positive feedback loop with renewables integration, given that e-mobility is a power-dense, mobile and controllable load.

Cars, including EVs, are currently parked on average over 90% of their lifetime (Barter, 2013). This, combined with their storage capacity, could make EVs an attractive flexibility solution to support system operations. The vehicles can become grid-connected storage units with a potential to provide a broad range of services to the system. Smart charging not only mitigates EV-caused demand peaks (mainly at the local grid level), but also can adjust the load curve to better integrate VRE.

Figure 3 illustrates how smart charging can integrate solar and wind generation in the grid by adjusting the charging profile of the EV to resource availability. As observed, smart charging strategies would differ according to the power system's conditions, including the renewable energy generation mix, load profile and interconnections available.

Smart charging reduces the costs associated with reinforcing local electricity grids. Unlike uncontrolled charging, it decreases simultaneity and lowers peaks in demand.

Figure 3: Smart charging for solar and wind generation profiles



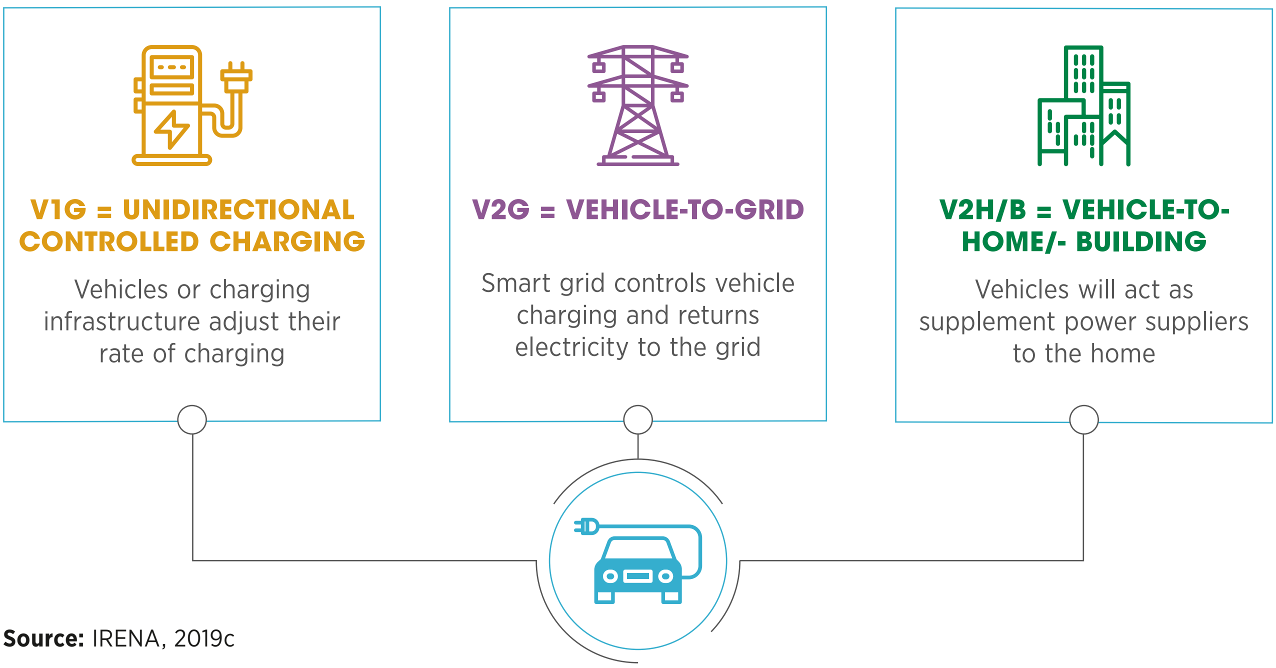
Source: IRENA, 2019c

Provision of services to the power system

Smartly charged EVs can help reduce VRE curtailment, improve local consumption of VRE production, avoid investment in peaking generation capacity and mitigate grid reinforcement needs.

Standing idle while parked for most of the time, EVs could provide a range of services to the power system, depending on the smart charging approach: unidirectional controlled charging (V1G), vehicle-to-grid (V2G) or vehicle-to-home/-building (V2H/B), as illustrated in Figure 4.

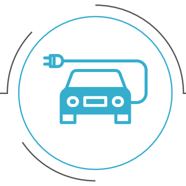
Figure 4: Forms of smart charging



Source: IRENA, 2019c

Adjusting their charging patterns, given that EVs currently are idle in parking for most of the time (90–95% of the time for most cars), could contribute to both system and local flexibility, as Figure 5 illustrates.

Figure 5: Services EVs can provide to the power system



SYSTEM FLEXIBILITY		LOCAL FLEXIBILITY	
Wholesale market	**Transmission System Operator**	**Distribution System Operator**	**Behind-the-meter**
• Peak-shaving • Portfolio balancing	• Frequency control • (primary, secondaryand tertiary reserve) • Other ancillary services (*e.g.*, voltage management, emergency power during outages)	• Voltage control • Local congestion and capacity management	• Increasing the rate of Renewable Energy self-consumption • Arbitrage between locally produced electricity and electricity from the grid • Back-up power

Peak shaving (system level/wholesale market): This involves flattening the peak demand and filling the "valley" of demand by incentivising late morning/afternoon charging in systems with large penetration of solar, and nighttime charging that could be adjusted following nighttime wind production, as cars are parked for a longer time than they need to fully charge. Early-evening charging that may otherwise increase peak demand would be deferred in this way. Consequently, this would defer investments for building additional peak capacity (Weiller and Sioshansi, 2016).

Ancillary services (system and local levels/ transmission and distribution system operators): This involves supporting real-time balancing of grids by adjusting the EV charging levels to maintain steady voltage and frequency. While flexibility has been well-developed at the system level by transmission system operators, distribution system operators are mostly not yet equipped with flexibility from distributed energy resources for operating their grids, despite the high number of demonstration projects that have been conducted and the intense regulatory discussions in several countries (mainly in Europe and the US).

Behind-the-meter optimisation and "back-up power" (local level/consumers and prosumers): This includes increasing self-consumption of locally produced renewable electricity as well as lowering dependence on the electricity grid and reducing the energy bill by buying low-cost electricity from the grid at off-peak hours and using it to supply homes when the electricity tariff is higher (during evenings).

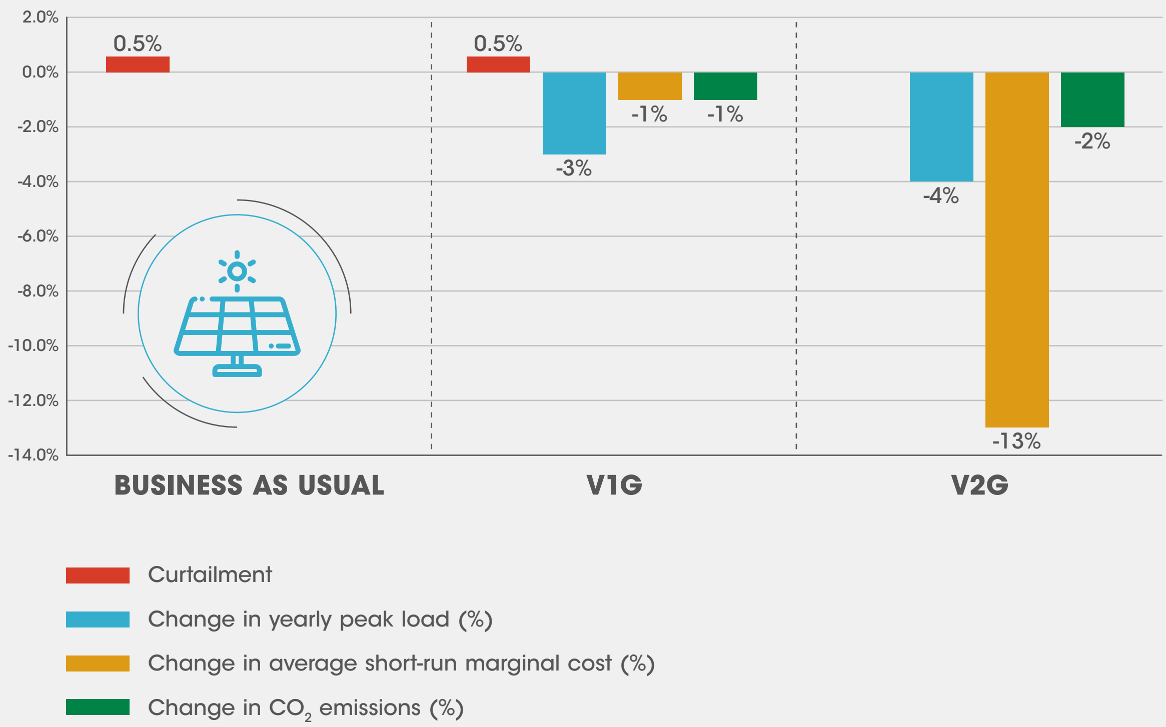
In addition, the EV battery can be used after it has been removed from the vehicle. An EV battery typically will be replaced when the capacity declines to 70–80% (that is, when it may no longer be sufficient for daily mileage); however, the performance is still sufficient for energy storage systems. This offers a lifetime extension of the battery of up to 10 years (Reid and Julve, 2016). With rising EV stocks, the number of potentially available second-use batteries will increase. Acting as stationary storage appliances after being removed from the vehicles, the batteries can further contribute to power system transformation (see the Innovation Landscape brief *Behind-the-meter batteries* [IRENA, 2019d]).

Potential impact on power sector transformation

Smart charging of EVs could have a great impact on the integration of VRE, both in system operation and in long-term expansion plans.

An IRENA study analysed the impact of V1G and V2G charging in comparison to no smart charging in an isolated solar-based system (IRENA, 2019c). In Figure 6, different indicators illustrate the impact of smart charging services in a solar-based system in 2030. **Smart charging cuts peak load, reduces curtailment and allows higher integration of low-cost PV electricity.** This can help displace more expensive generation and can lower electricity prices.

Figure 6: Short-term impact of EV charging



Other recent studies have explored the potential of smart charging and its contribution to power sector transformation, for example:

- Modelling of EVs in New England in the US showed that a 25% EV share in the system charged in an uncontrolled fashion would **increase peak demand by 19%**, requiring significant investment in grid and generation capacities. However, spreading the load over the evening hours could **cut the increase in peak demand to between 0% and 6%**. Charging only at off-peak hours could avoid any increase at all in peak demand (RMI, 2016a).

- Another study simulates the impact of 23% EV penetration in the fleet in 2030 in California (US), with both controlled and optimised charging modes. A big difference in peak load is found in the two scenarios. While all EVs in uncontrolled charging mode would **increase the peak load by 11.14%,** with **smart charging,** EVs would **increase the peak load by only 1.33%** (RMI, 2016b).

- With 100% EV penetration in 2050 in Denmark, Germany, Norway and Sweden, if no V2G is applied, the peak of the **net load curve would increase by 20%** in Scandinavia and Germany (from 127 GW to 152 GW). However, if V2G is applied, passenger EVs will smoothen the net load curve in the Scandinavian and German electricity system so that the hour with **maximum net load is reduced by 7%** (from 127 GW to 118 GW) (Taljegard, 2017).

- A study done for the island of Barbados, with solar and wind supply covering 64% of demand and more than 26 000 EVs by 2030, demonstrates a **five-times increase in production costs** with uncontrolled charging compared to the most efficient smart charging strategy (Taibi and Fernández, 2017).

- A study from 50Hertz, one of Germany's transmission system operators, concludes that the number of EVs in the country in 2035 would have a limited impact on peak demand (approximately 8%) if smart charging is in place. The study also concludes that distribution grid infrastructure might limit high EV penetration rates in residential areas, if distribution system operators do not identify shortages in their grid and **implement smart charging also considering location constraints, not only time constraints** (Schucht, 2017).

- A McKinsey study on EV integration in Germany concludes that when local EV penetration hits 25%, peak load can grow by 30% in the absence of smart charging. Using a V1G strategy and time-of-use tariffs, the **peak load increase can be reduced by 16%** (McKinsey & Company, 2018).

- A Dutch field test showed that uncontrolled charging might lead to local black-outs and imbalance between the three phases in a low-voltage grid. Thus, **smart charging is required to avoid expensive reinforcement costs** for seldom but high peaks resulting from uncontrolled or market-based steering of EVs (Hoogsteen *et al.*, 2017).

- One million EVs in the Guanzhou region in China will increase the peak load of the grid by 15% without any charging control. However, the difference between peak and valley load will be reduced by 43% without V2G technology, while **it can be reduced by 50% if V2G is available** (Chen and Wu, 2018).

- Stromnetz Hamburg, the distribution system operator in Hamburg, Germany, partnered with Siemens to install 30 control units and to monitor the private EV-charging infrastructure loads. This will help the operator anticipate congestion issues and plan the network based on the load profiles. The estimated cost of this solution is around EUR 2 million, which is **just 10% of the cost of reinforcing the cables** in a conventional solution (Pfarrherr, 2018).

- A study that assessed the impact of introducing 2.5 million EVs in Turkey, reaching a penetration level of 10% in the total stock, concluded that this would **increase the peak load by 12.5% with uncontrolled charging**. However, with **smart charging, the peak load would increase only by 3.5%** (Saygin *et al.*, forthcoming).

III. KEY FACTORS TO ENABLE DEPLOYMENT

An intelligent exchange of information, standardised communication protocols as well as connecting EVs and charging points with the help of smart meters and other intelligent infrastructure are needed to optimise the system.

Charging infrastructure

Developing charging infrastructure requires major investments, and currently there are limited business models for private investment. Governments can incentivise the installation of charging stations either at residential or public access locations. The support for the development of charging infrastructure can be first based on ambitious EVs targets and then focused on specific funding for implementation projects.

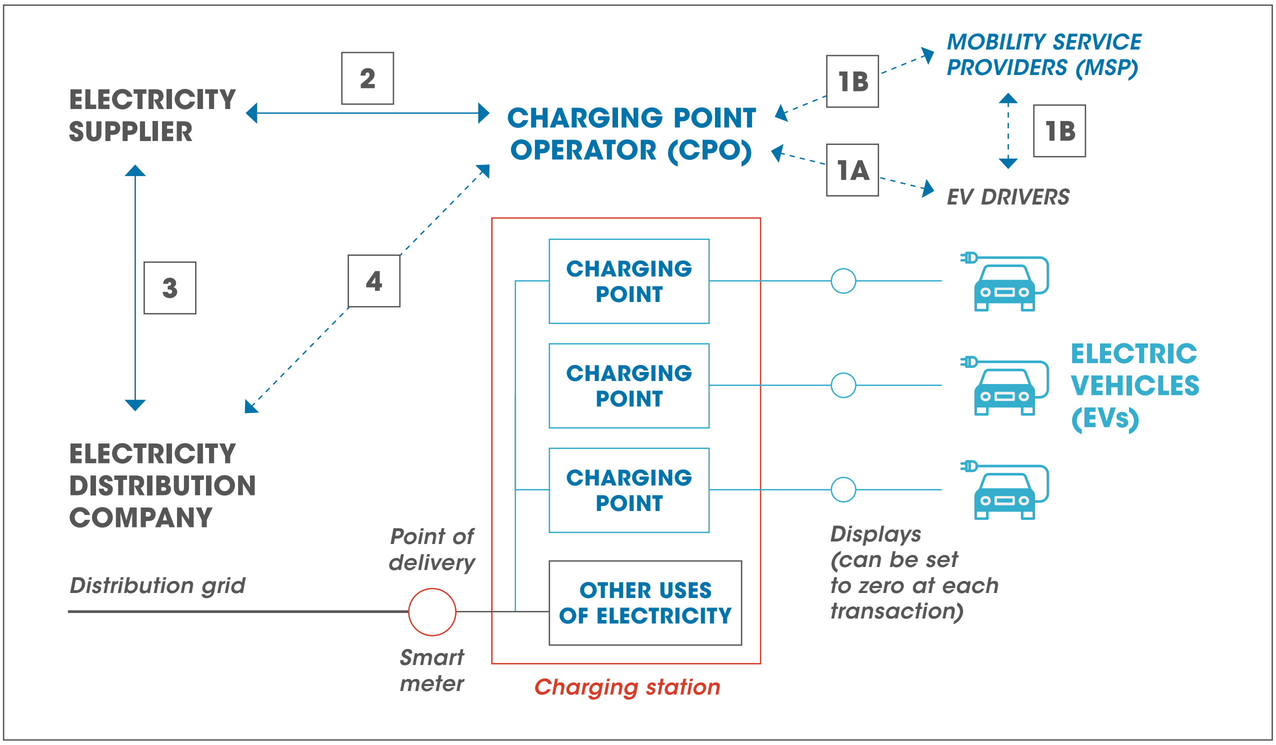
In addition, the need to understand how to best charge, aggregate and control the EV load on the grid is a fundamental and ongoing issue. This would impact important decisions in the development of charging infrastructure – such as where to best place the charging points, which technology to use and how to combine slow smart chargers with fast chargers, to best meet consumer's immediate needs.

In the UK, the Office of Low Emission Vehicles provides grant schemes to cover part of the cost associated with installing EV charging infrastructure. The Electric Vehicle Homecharge Scheme provides residential customers grants that can cover up to 75% of the total procurement and installation costs. From July 2019, only home charging points using "smart" technology will be eligible for this government funding. Smart charging points are defined as charging points that can receive, understand and respond to signals sent by energy system operators or third parties to indicate when is a good time to charge or discharge in relation to overall energy supply and demand (RECC, 2019). A similar scheme is designed for local authorities that wish to install on-street residential charging points. Under the Working Charging Scheme, businesses, charities and public sector organisations can apply for a voucher of GBP 300 per socket up to a limit of 20 sockets (UK Government, 2016).

Define stakeholders' roles and responsibilities

Another important and defining characteristic of smart charging is that it finds itself at the junction between the electricity market and e-mobility. Unlike "traditional" charging, where the e-mobility market (EV drivers, charging point operators, mobile service providers) acts independently of the electricity market, smart charging requires a close co-ordination between the two in order to both accommodate e-mobility requirements in the power system and provide the power system with the needed flexibility. Figure 7 illustrates the relationship between the actors in the two markets, where clear roles and responsibilities need to be defined for each of them.

Figure 7: Contractual relationship between actors involved in electric mobility



Legend: *1A: EV Driver – Chargning Point Operator (directly); 1B: EV Driver - Charging Point Operator (intermediated by Mobility Service Provider); 2: Charging Point Operator – Electricity Supplier; 3: Electricity supplier – Electricity distribution company; 4 Electricity distribution company – Charging Point Operator (only for connection)*

a: Directive 2014/94/EU of the European Parliament and of the Council of 22 October 2014 on the deployment of alternative fuels infrastructure.

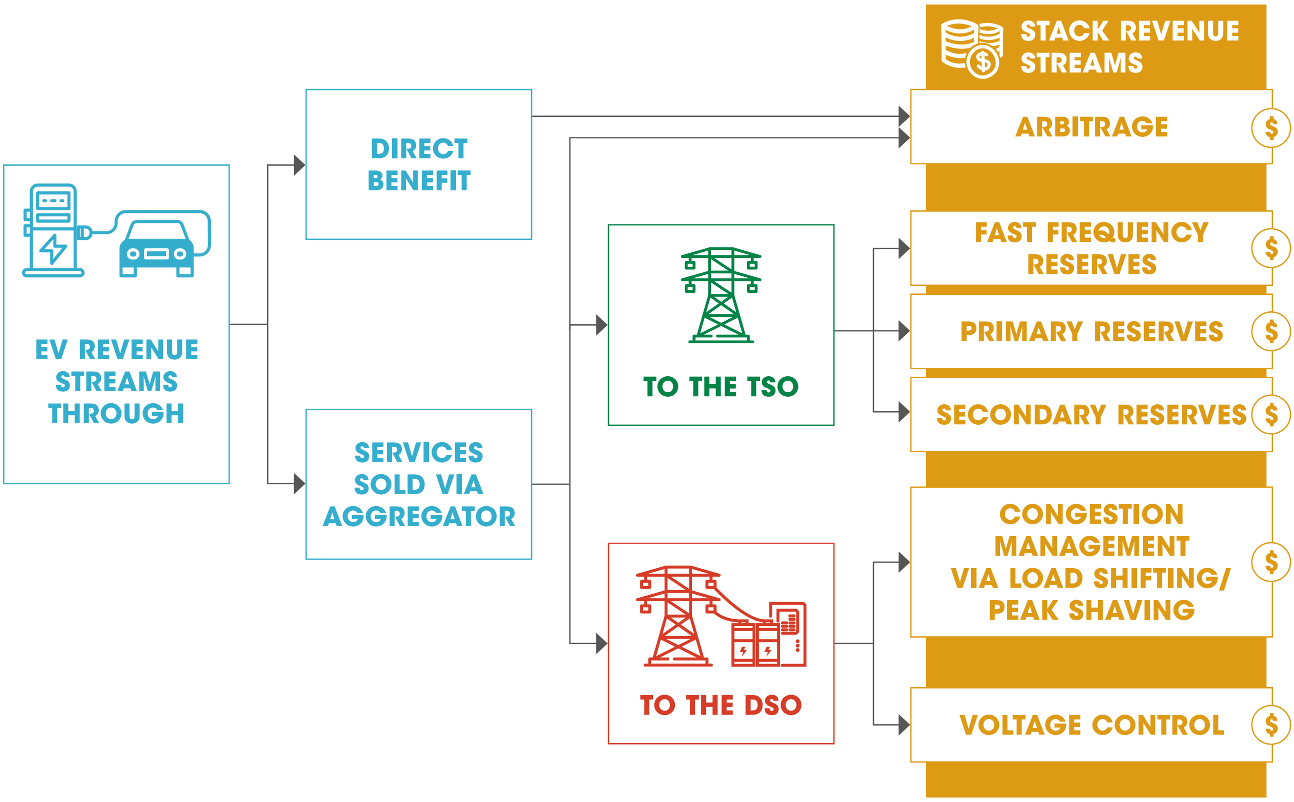
Note: TSO = Transmission System Operator; DSO = Distribution System Operator
Source: IRENA, 2017

Key roles here are the "charging point operator" (CPO) and the "mobility service provider" (MSP). On the one hand, to unlock the potential of smart charging schemes and V2G use cases, charging a fleet of EVs could be controlled by a CPO. The role of the CPO can be taken by the utility itself, the electricity supplier, an e-mobility organisation or even a company that is specialised in demand response services. On the other hand, the MSP could act as an intermediary between the CPO and EV drivers.

Design regulation for vehicle-grid integration

Smart charging will not "just happen" without the right incentives in the form of dynamic price signals. In a similar vein, V2G will not materialise without the possibility to "stack revenue" from multiple revenue streams, providing flexibility at both the system and local levels. Figure 8 depicts the possible revenue streams for EVs, which need to be enabled to incentivise smart charging.

Figure 8: Possible EV revenue streams that can be stacked



Note: TSO = Transmission System Operator; DSO = Distribution System Operator
Source: IRENA, 2019c

This will not happen without well-functioning electricity markets. Competitive wholesale and retail markets are not always in place today, even in the emerging e-mobility markets. In most countries, wholesale electricity markets exist, but competitive balancing/ancillary service markets and retail markets are often missing – that is, they are still regulated services executed centrally by a transmission system operator.

Even where such markets are in place, their design will need to develop, and regulations will need to be adjusted to provide incentives for the valuation of EV grid services, including:

- Adjustment of market thresholds and access conditions for different wholesale segments. Even in markets that explicitly allow aggregation access, minimum capacity and availability requirements for major grid services remain designed for large-scale power plants.
- Avoiding double charging of storage for the grid that penalises V2G as well as second-life batteries.
- Updating outdated regulations prohibiting the resale of electricity from the grid without a supplier, in order to account for EVs.

Aggregators

EV batteries can provide the fast response needed for some ancillary services, but their power capacity is limited; thus a single EV cannot provide these services for the period of time needed by the power system. However, when EVs are aggregated they can complement one other, resulting in a virtual power plant with a fast response and the ability to provide services for the needed period of time.

Aggregator business models facilitate the use of EVs as a source of flexibility. At least 1–2 MW capacity must be traded to make EV power provision viable at the wholesale level. This requires the aggregation of around 500 vehicles and their charging points.

Virtual Power Plant operator Next Kraftwerke, and Jedlix, an electric vehicle (EV) aggregator and smart charging platform provider, have launched an international pilot project which uses EV batteries to deliver secondary control reserve to TenneT, the transmission system operator in Netherlands. Jedlix will be able to combine user preferences, car data, and charging station information to provide a continuous forecast of the available capacity. This is then used by Next Kraftwerke in the bidding process of TenneT for procuring grid services (NextKraftwerke, 2018).

ICT control and communication protocols

In addition, in order to optimise the system and facilitate information sharing among all actors, communication protocols need to be developed. Smart charging involves the charging of an EV controlled by bidirectional communication between two or more actors to optimise all customer requirements, as well as grid management, and energy production including renewables with respect to system costs, limitations, reliability, security and safety.

For example, the Open Charge Alliance developed the Open Charge Point Protocol (OCPP) as a uniform solution for communication between a charge point and a central system. With this protocol, it allows for connecting any central system with any charge point, regardless of the vendor. The control mechanism can be enabled by the grid, the charging point or the vehicle itself.

Meanwhile, a communication system with the grid allows the charging process to take into account actual grid capabilities (intelligent algorithms can be distributed at all three levels) as well as customers' preferences. Price or control signals can be communicated through an information and communications technology (ICT) infrastructure (for example, intelligent metering system, communication between charging stations and back-end systems) in order to allow algorithms to take into consideration generation and grid constraints, as well as to enable customers to benefit from price opportunities.

Big data and artificial intelligence for smart charging

Smart charging through use of V2G integration technologies is a means of managing EV loads, either by customer response to price signals or by an automated response to control signals reacting to the grid or market situations, or by a combination of the two. This needs to be done while respecting the customer's needs for vehicle availability. It consists of shifting some charging cycles in time or modulating the power in function of some constraints (for example, connection capacity, user needs, real-time local energy production).

Advancements in big data and artificial intelligence could facilitate and optimise the services provided by smart charging solutions. ICT advancements including data management and data analytics from drivers, charging patterns, CPOs and charging stations would enhance smart charging functionalities and atomise the provision of services to the grid. In addition, digital technologies and data analytics will enable mobility demand with power supply patterns to be as compatible as possible and to decide about the most optimal locations for charging points.

If direct control mechanisms enabled by the EV and the charging point are in place, further services could be provided to the grid without affecting consumers' needs. For instance, customers could set the car's departure time and/or the required battery capacity reserve. The charging station then determines the current battery status and calculates the energy necessary to reach the desired state in the most optimal way to improve the power system's economic and environmental performance.

IV. CURRENT STATUS AND EXAMPLES OF ONGOING INITIATIVES

The table below captures useful indicators about EVs and smart charging. Some case studies follow.

Table 1 Key indicators for EVs and smart charging

Number of EVs on the road at the beginning of 2019	Worldwide: 5.6 million China: 2.6 million US: 1.1 million
Compound annual growth rate of EV sales between 2012 and 2017	57%
EV share of total light-duty vehicles (LDVs) sold in 2017	1.3%
Largest EV markets in terms of units sold in 2017	China, Norway, US (Norway has the highest penetration of EVs in overall LDV sales)
LDV chargers in 2018 (globally)	5.2 million
Publicly accessible chargers in 2018 (globally)	540 000
Fast chargers for buses in 2018 (globally)	157 000

Source: IRENA, 2019c; IEA, 2019

Vehicle-grid integration project in San Diego (US)

San Diego Gas & Electric (SDG&E) launched a vehicle-grid integration pilot project that tests making fleets of EVs available as dispatchable distributed energy resources to improve the stability of the grid. SDG&E will install and operate 3 500 charging stations, mainly slow-charging stations, throughout the San Diego region. The programme explores dynamic pricing and, through an app, incentivises charging activities at moments of high renewable energy supply (Turpen, 2016). Dynamic hourly rates are posted on a day-ahead basis, and they reflect both the system and local grid conditions. An app matches customers' preferences with those prices. For simple time-of-use, bigger effects were recorded for customers with separate EV-only meters (RMI, 2016a).

Nuvve the vehicle-to-grid experience (US)

One advanced player in the V2G technology is Nuvve. Nuvve supplies a wide range of services to the power system including frequency and supply reserve capacity in different markets. It has been participating in the PJM (Pennsylvania-Jersey-Maryland) frequency market in the US since 2009. Customers just provide information on when they need the vehicle, and when the battery is charged enough, the optimisation software can choose to supply electricity back to the grid, or provide other services.

Nuvve announced the intention to roll out 1500 smart chargers in the UK with V2G capability. The idea is to offer the chargers to EDF Energy's business customers that use electric cars. Estimations show that the chargers would be able to supply up to 15 MW of power (assuming that the cars are connected to the chargers and charged sufficiently). On average the resulting power would be some 10 kW per car/charger (Kane, 2018).

Vehicle-to-grid projects in Hamburg (Germany)

In February 2019, the City of Hamburg launched the ELBE project, which focuses on funding the installation of EV charging stations at buildings and on commercial premises. The project includes the application of V2G technology and load-dependent tariffs, where EVs are considered as controllable consumption.

Parker project (Denmark)

The Danish project, Parker, is an example of a V2G project that uses smart charging technology and relies on co-operation between the automotive and power industries to demonstrate the ability of EVs to support and balance power systems based on renewable energy. Grid integration specialists such as Enel, Nuvve and Insero, as well as the auto manufacturers Nissan, Mitsubishi and PSA Groupe, have demonstrated that state-of-the-art vehicles from various auto manufacturers can contribute to supporting the electricity grid, providing services such as frequency and voltage control via V2G technology.

The project shows that V2G has the potential to play a significant role in providing grid flexibility, and increasing the vehicle's revenue, but that technical challenges remain, including uncertainty about degradation of batteries, lack of standardisation of communication and lack of consumer knowledge of the V2G system (Bach Andersen *et al.*, 2019). The yearly revenue per car in Denmark is estimated to be between EUR 1700 and EUR 2500, depending on the availability of wind resources (Bach Andersen *et al.*, 2019).

Other examples of smart charging deployment from different parts of the world, listed by the type of smart charging implemented, are provided in Table 2.

Other examples of EV Smart Charging projects

Table 2 Overview of smart charging deployment and pilot projects

Type of charging	Examples of projects
Uncontrolled time-of-use tariffs	China, Germany, Japan, UK, US
Basic control	My Electric Avenue, Scottish and Southern Energy Power Distribution and led by EA Technology, UK (100 households testing Esprit system) Pepco, Maryland, US (200 households) United Energy – Victoria, Australia (2013)
Unidirectional controlled (V1G)	Green eMotion project, EU (2015): reduction of grid reinforcement cost by 50% Sacramento Municipal Utility, US: reduction of grid upgrade expense by over 70%
Bidirectional vehicle-to-grid (V2G)	eVgo and University of Delaware project, US, with transmission system operator PJM Interconnection – commercial operation Nuvve, Nissan and Enel, in England and Wales, with transmission system operator National Grid – operating pre-commercially Nuvve, DTU, Nissan, PSA and Enel project in Denmark, with transmission system operator energinet.dk ("Parker project") – operating trial Nuvve, The New Motion, Mitsubishi project in the Netherlands, with transmission system operator TenneT – commercial trial Jeju, Republic of Korea project developing fast and slow V2G; Toyota city project with 3 100 EVs Renault, Elaad NL and Lombo Xnet project, Utrecht, the Netherlands, AC V2G
Bidirectional vehicle-to-X (*e.g.*, V2H)	ElaadNL and Renault, Utrecht, the Netherlands: 1 000 public solar-powered smart charging stations with battery storage around the region in the largest smart charging demonstration to date, although not all of them are V2X chargers. Increase of self-consumption from 49% to 62–87% and decrease of peak by 27–67%. DENSO and Toyota intelligent V2H (HEMS and V2G integrated model), Nissan (V2B) – all Japan
Dynamic pricing with EVs (controlled)	Nord-Trøndelag Elektrisitetsverk Nett in Norway San Diego Gas & Electric in California, with prices posted one day ahead
Second-life battery	BMWi and PG&E Charge Forward Pilot Program in California

V. IMPLEMENTATION REQUIREMENTS: CHECKLIST

TECHNICAL REQUIREMENTS	**Hardware:** • Widespread adoption of EVs. • Public and private charging infrastructure – smart charging points. • Smart meters – required for supplying interval values for net consumption and net production.
	Software: • Smart charging services such as energy and power flow management systems that allow for optimal EV charging, ICT systems, intelligent charging infrastructure or advanced algorithms for local integration with distributed energy sources.
	ICT structure and development of communication protocols: • Agree and develop common interoperable standards (both at physical and ICT layers) as well as clear definitions and roles for actors and smart charging. • Develop a uniform solution for the method of communication between charge points and the central power system, regardless of the vendor.
POLICIES NEEDED	**Stable, supportive policies for e-mobility and smart charging**
	Strategic policies could include: • Prioritisation of demonstration and commercialisation: Increased co-operation between public and private actors could enable the roll-out of large-scale demonstration and pilot projects. • Win-win synergies and exchanges between the electricity, automotive and manufacturing sectors: the electricity industry should increasingly engage with e-mobility stakeholders in raising awareness and developing best practices with a focus on customer opportunities.

REGULATORY REQUIREMENTS

Wholesale market:

- Allow EVs, through aggregators or individually, to provide services in the ancillary service market and wholesale market.
- Enable revenue streams to incentivise smart charging of EVs.

Distribution system:

- Innovative grid fees for distribution networks (possibly special tariffs for transport) given a suitable framework for smart meters.

Retail market:

- Efficient price signals (such as time-of-use tariffs) or other load management schemes to incentivise smart charging.
- Understand customer behaviour and create awareness of the possibilities to use load management.

STAKEHOLDER ROLES AND RESPONSIBILITIES

State institutions:

- National governments could sponsor the projects and provide subsidies for deployment of charging points.
- Local and regional authorities could co-finance the project.

Electricity market:

- Distribution system operators can seek support from e-mobility service providers and/or ICT companies in the delivery of smart charging services through their customers to ease the cost of technology adoption and to delay/avoid grid reinforcements.
- Energy retailers can develop smart charging as a measure to support their power plants portfolio strategy, particularly at the local level, and as a possible revenue stream coming from ancillary services sold to the transmission system operators.

E-mobility market:

- Incentivise electric mobility market participants to invest in smart charging solutions and services.
- Provide incentives to e-mobility customers, via contractual benefits (*e.g.*, price signals), to access smart charging services.
- Charging spot operators need to fulfil their contractual commitments while considering charging requests from consumers and optimising their costs based on electricity market signals.
- E-mobility service providers request charging access following the demand from their e-mobility customers. The charging requests might be executed either on a charging infrastructure owned by a third party, the charging spot operators, or owned by the e-mobility service provider itself, in the case when it also plays the role of charging spot operator.

ACRONYMS AND ABBREVIATIONS

BMWi	Germany Federal Ministry for Economic Affairs and Energy
CO_2	carbon dioxide
CPO	charging point operator
DSO	distribution system operator
EU	European Union
EUR	Euro
EV	electric vehicle
GBP	British pound
ICT	information and communications technology
KPI	key performance indicator
LDV	light-duty vehicle
MSP	mobility service provider
OCPP	Open Charge Point Protocol
PG&E	Pacific Gas & Electric
SDG&E	San Diego Gas & Electric
UK	United Kingdom
US	United States
V1G	unidirectional vehicle-to-grid
V2B	vehicle-to-building
V2G	bidirectional vehicle-to-grid
V2H	vehicle-to-home
V2X	vehicle-to-X
VRE	variable renewable energy

UNITS OF MEASUREMENT

GW	gigawatt
kW	kilowatt
MW	megawatt
TWh	terawatt-hour

BIBLIOGRAPHY

Bach Andersen, P. *et al.* (2019), *Parker Project Final Report*, Energy Technology Development and Demonstration Program (EUDP).

Barter, P. (2013), "'Cars are parked 95% of the time' Let's check!" Reinventing Parking, https://www.reinventingparking.org/2013/02/cars-are-parked-95-of-time-lets-check.html.

Chen, L. and Z. Wu (2018), "Study on effects of EV charging to global load characteristics via charging aggregators", *Energy Procedia*, vol. 145: 175–180.

Enel (2016), "Nissan, Enel and Nuvve operate world's first fully commercial vehicle-to-grid hub in Denmark", https://www.enel.com/media/press/d/2016/08/nissan-enel-and-nuvve-operate-worlds-first-fully-commercial-vehicle-to-grid-hub-in-denmark.

Eurelectric (2015), *Smart charging: Steering the change, driving the change*, Eurelectric, Brussels.

Hoogsteen, G. *et al.* (2017), *Charging electric vehicles, baking pizzas and melting a fuse in Lochem*, 24th International Conference on Electricity Distribution CIRED, Glasgow, 12–15 June.

IEA (2019), *Global EV Outlook 2019*, International Energy Agency, Paris.

IRENA (2019a), *Innovation landscape for a renewable-powered future: Solutions to integrate variable renewables*, International Renewable Energy Agency, Abu Dhabi, https://www.irena.org/-/media/Files/IRENA/Agency/Publication/2019/Feb/IRENA_Innovation_Landscape_2019_report.pdf.

IRENA (2019b), *Global energy transformation: A roadmap to 2050*, International Renewable Energy Agency, Abu Dhabi, https://www.irena.org/publications/2019/Apr/Global-energy-transformation-A-roadmap-to-2050-2019Edition.

IRENA (2019c), *Innovation outlook: Smart charging for electric vehicles*, International Renewable Energy Agency, Abu Dhabi, https://www.irena.org/-/media/Files/IRENA/Agency/Publication/2019/May/IRENA_Innovation_Outlook_EV_smart_charging_2019.pdf.

IRENA (2019d), the Innovation Landscape brief *Behind-the-meter batteries*, International Renewable Energy Agency, Abu Dhabi.

IRENA (2017), *Adapting market design to high shares of variable renewable energy.* International Renewable Energy Agency, Abu Dhabi

Kane, M. (2018), "Electric cars will be able to supply up to 15 MW of power", InsideEVs, https://insideevs.com/news/340839/edf-energy-amp-nuvve-to-install-1500-v2g-chargers-in-uk/.

Lambert, F. (2016), "Electric vehicle smart charging to go nationwide in the Netherlands, taking advantage of solar and wind energy", Electrek, https://electrek.co/2016/10/18/electric-vehicle-smart-charging-to-go-nationwide-in-netherlands.

McKinsey & Company (2018), "The potential impact of electric vehicles on global energy systems", https://www.mckinsey.com/industries/automotive-and-assembly/our-insights/the-potential-impact-of-electric-vehicles-on-global-energy-systems.

NextKraftwerke, 2018. "Next Kraftwerke and Jedlix launch initiative to use electric car batteries for grid stability". www.next-kraftwerke.com/news/next-kraftwerke-jedlix-launch-initiative-to-use-electric-car-batteries-for-grid-stability.

Pfarrherr, B. (2018), *Controlling private e-mobility charging points in public low voltage grids*, Stromnetz Hamburg, Vienna.

RECC, 2019, "An introduction to Electric Vehicle home chargepoints", Renewable Energy Consumer Code, www.recc.org.uk/images/upload/news_240_Consumer-Guidance-on-EV-Home-Chargepoints-14.pdf.

Reid, G. and J. Julve (2016), *Second-life batteries as flexible storage for renewable energies, Bundesverbandes Erneuerbare Energie e. V. and Hannover Messe*, Berlin, https://speicherinitiative.at/assets/Uploads/05-SecondLife-Batterienflexible-EE-Speicher.pdf.

RMI (2016a), *A review of alternative rate designs: Industry experience with time-based and demand charge rates for mass-market customers*, Rocky Mountain Institute, Basalt, Colorado, US, https://rmi.org/wp-content/uploads/2017/04/A-Review-of-Alternative-Rate-Designs-2016.pdf.

RMI (2016b), *Electric vehicles as distributed energy resources*, Rocky Mountain Institute, Basalt, Colorado, US, https://www.rmi.org/wp-content/uploads/2017/04/RMI_Electric_Vehicles_as_DERs_Final_V2.pdf.

Saygin, D., Tör, O.B., Teimourzadeh, S., Hildermeier, J., Kolokathis, C. (Forthcoming), *Transforming Turkey's transport sector: Assessing the impact of EVs on distribution grids.* SHURA Energy Transition Center, Istanbul.

Schucht, B. (2017), *The development of e-mobility from the perspective of a German TSO*, 50 Hertz.

Taibi, E. and Fernández, C. (2017), *The impact of electric vehicles deployment on production cost in a Caribbean Island country*, IRENA Innovation and Technology Centre (IITC), Bonn, http://mobilityintegrationsymposium.org/wp-content/uploads/sites/7/2017/11/2B_5_EMob17_009_paper_Taibi_Emanuele.pdf.

Taljegard, M. (2017), *The impact of an electrification of road transportation on the electricity system, Chalmers University of Technology*, Gothenburg, Sweden.

Turpen, A. (2016), "California to get utility-owned EV charging stations with dynamic pricing", New Atlas, https://newatlas.com/california-electric-car-utility-charging/41585/.

UK Government (2016), "Grant schemes for electric vehicle charging infrastructure", http://www.gov.uk/government/collections/government-grants-for-low-emission-vehicles.

US Department of Energy (2014), *Evaluating electric vehicle charging impacts and customer charging behaviors – Experiences from six smart grid investment grant projects*, US Department of Energy, Washington, DC, US.

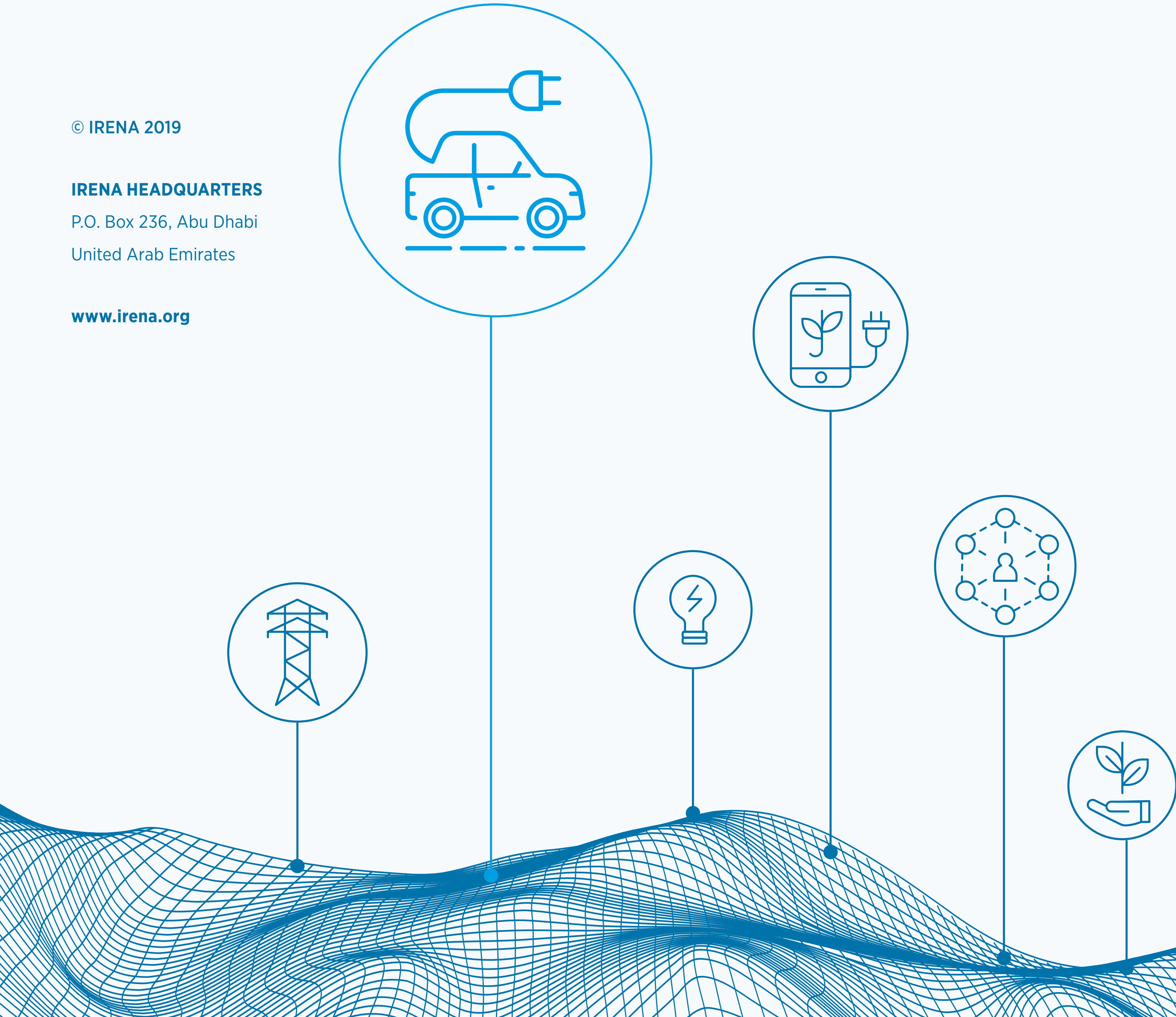
Voelcker, J. (2012), "Nissan Leaf-to-Home power station: Will it make it to U.S.?" Green Car Reports, https://www.greencarreports.com/news/1079955_nissan-leaf-to-home-power-station-will-it-make-it-to-u-s.

Weiller, C. and R. Sioshansi (2016), "The role of plug-in electric vehicles with renewable resources in electricity systems", *Revue d économie industrielle*, vol. 148: 291–316.

Wenyu, S., 2017. "China builds world's largest EV charging network with 167,000 stations". People's Daily Online. http://en.people.cn/n3/2017/0906/c90000-9265487.html.

IRENA
International Renewable Energy Agency

ELECTRIC-VEHICLE SMART CHARGING
INNOVATION LANDSCAPE BRIEF



IRENA HEADQUARTERS
P.O. Box 236, Abu Dhabi
United Arab Emirates

www.irena.org

International Renewable Energy Agency

INTERNET OF THINGS

INNOVATION LANDSCAPE BRIEF

ISBN 978-92-9260-142-3

Citation: IRENA (2019), *Innovation landscape brief: Internet of Things,* International Renewable Energy Agency, Abu Dhabi.

ACKNOWLEDGEMENTS

This report was prepared by the Innovation team at IRENA's Innovation and Technology Centre (IITC) with text authored by Sean Ratka, Arina Anisie, Francisco Boshell and Nadeem Goussous.

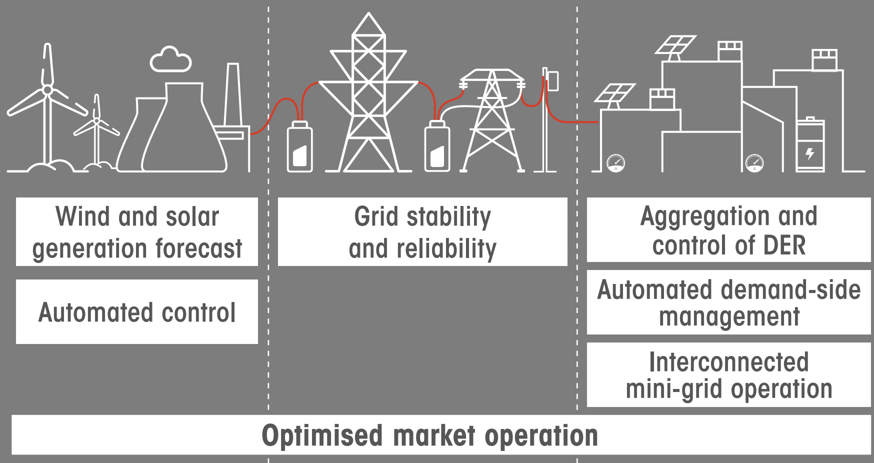
This report benefited from the input and review of experts: Tiago Maouras (EDP), Stephen Woodhouse and Tom Ingelse (Poyry), Jaideep Sandhu (Engie), along with Emanuele Taibi, Elena Ocenic, Nina Litman-Roventa and Paul Komor (IRENA).

Report available online: www.irena.org/publications
For questions or to provide feedback: publications@irena.org

1 BENEFITS

IoT devices enable "smart grids" through the collection, transmission and use of large amounts of data, intelligently integrating grid-connected users, optimising grid operation and increasing system flexibility

IoT benefits for solar and wind integration



DER = distributed energy resources

2 KEY ENABLING FACTORS

- Reaching technology maturity and reliability
- Ensuring data privacy
- Addressing cybersecurity challenges
- Developing communication procedures and protocols

3 SNAPSHOT

- → 75 billion devices could be connected worldwide by 2025
- → Most IoT projects in the power sector focus on demand-side applications (*e.g.*, smart homes)
- → Digital systems and data analytics can:
  - Reduce O&M costs
  - Boost renewable power generation
  - Reduce renewable power curtailment

WHAT IS THE INTERNET OF THINGS?

Smart devices monitor, communicate and interpret information from their surroundings in real time. The resulting Internet of Things (IoT) enables meaningful data gathering and system optimisation.

INTERNET OF THINGS

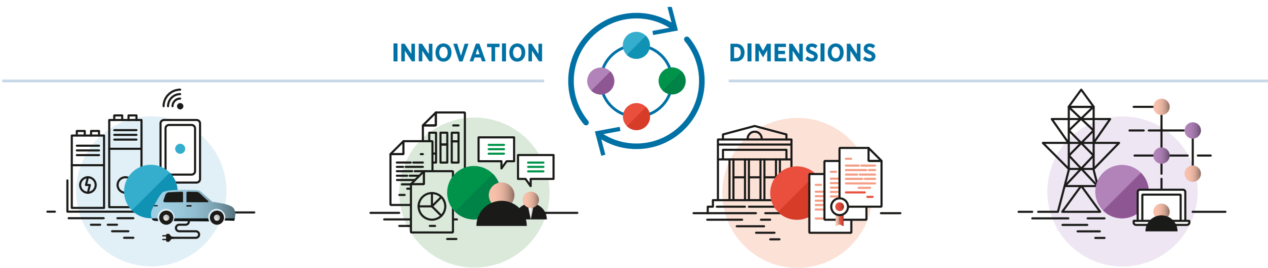
The Internet of Things (IoT) **enables smart grids.**
As power systems become increasingly complex and decentralised, IoT applications enhance the **visibility and responsiveness** of grid-connected devices.

ABOUT THIS BRIEF

This brief is part of the IRENA project "Innovation landscape for a renewable-powered future", which maps the relevant innovations, identifies the synergies and formulates solutions for integrating high shares of variable renewable energy (VRE) into power systems.

The synthesis report, *Innovation landscape for a renewable-powered future: Solutions to integrate variable renewables* (IRENA, 2019), illustrates the need for synergies among different innovations to create actual solutions. Solutions to drive the uptake of solar and wind power span four broad dimensions of innovation: enabling technologies, business models, market design and system operation.

Along with the synthesis report, the project includes a series of briefs, each covering one of 30 key innovations identified across those four dimensions. The 30 innovations are listed in the figure below.



ENABLING TECHNOLOGIES

1 Utility scale batteries
2 Behind-the-meter batteries

3 Electric-vehicle smart charging
4 Renewable power-to-heat
5 Renewable power-to-hydrogen

6 Internet of Things
7 Artificial intelligence and big data
8 Blockchain

9 Renewable mini-grids
10 Supergrids

11 Flexibility in conventional power plants

BUSINESS MODELS

12 Aggregators
13 Peer-to-peer electricity trading
14 Energy-as-a-service

15 Community-ownership models
16 Pay-as-you-go models

MARKET DESIGN

17 Increasing time granularity in electricity markets
18 Increasing space granularity in electricity markets
19 Innovative ancillary services
20 Re-designing capacity markets
21 Regional markets

22 Time-of-use tariffs
23 Market integration of distributed energy resources
24 Net billing schemes

SYSTEM OPERATION

25 Future role of distribution system operators
26 Co-operation between transmission and distribution system operators

27 Advanced forecasting of variable renewable power generation
28 Innovative operation of pumped hydropower storage

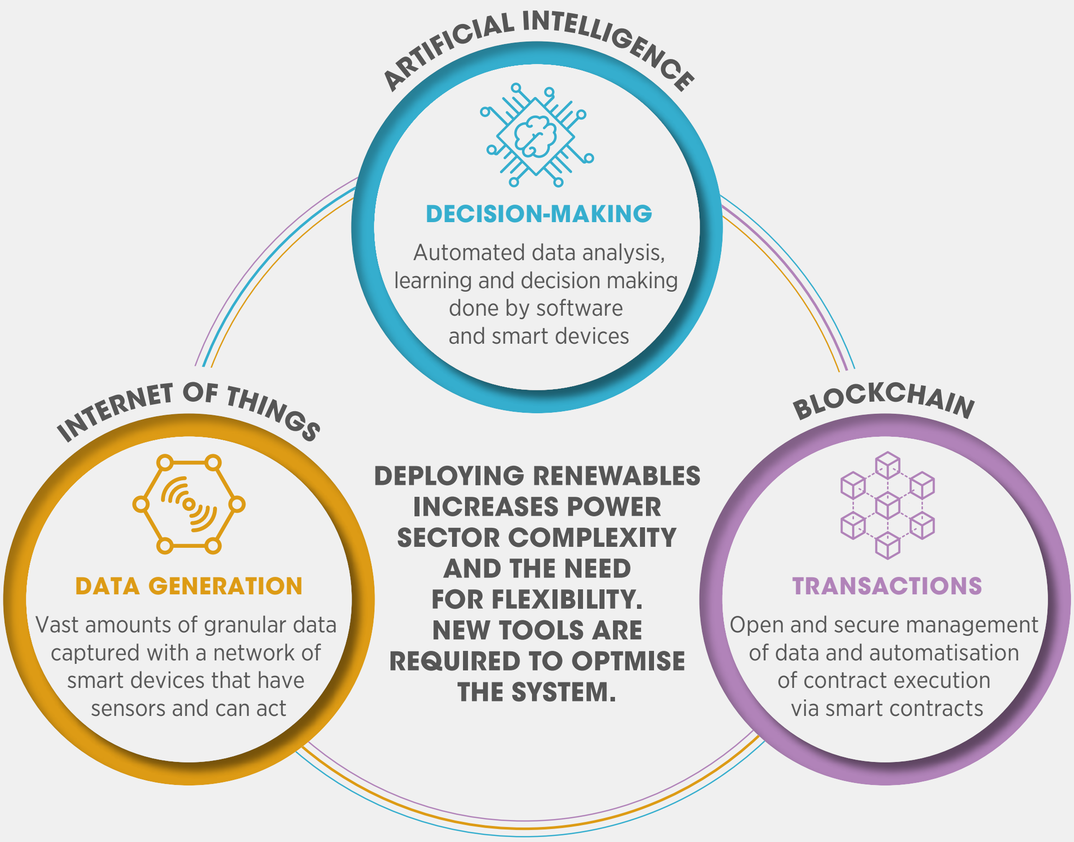
29 Virtual power lines
30 Dynamic line rating

Digitalisation to support VRE integration

Digitalisation is a key amplifier of the power sector transformation, enabling the management of large amounts of data and optimising increasingly complex systems. For the power sector, digitalisation is essentially converting data into value (IRENA, 2019a). The growing importance of digitalisation in the power sector is also a consequence of advances in two other innovation trends: decentralisation and electrification. Decentralisation is led by the increased deployment of small power generators, mainly rooftop solar photovoltaic (PV), connected to the distribution grid. Electrification of transport and buildings (heating and cooling) involves large quantities of new loads, such as electric vehicles, heat pumps and electric boilers. All these new assets on the supply and demand sides are adding complexity to the power sector, making monitoring, management and control crucial for the success of the energy transformation.

Digital technologies[1] can support the renewable energy sector in several ways, including better monitoring, operation and maintenance of renewable energy assets; more refined system operations and control closer to real time; implementation of new market designs; and the emergence of new business models. Within the context of the *Innovation landscape for a renewable-powered future* report, IRENA's analysis focuses on one concrete application for digital technologies: the integration of VRE technologies into power systems. Accordingly, three specific digital technology groups are studied further: 1) the internet of things (IoT); 2) artificial intelligence (AI) and big data; and 3) blockchain. The analysis indicates that none of these are silver bullets, but rather reinforce each other as part of a toolbox of digital solutions needed to optimise the operations of an increasingly complex power system based on renewable energy.

Figure 1: Increased power sector complexity requires a combination of digital innovations



1 These commonly include: digital twins; chatbots; the IoT; artificial intelligence and big data; distributed ledger technologies (DLT) such as blockchain; and augmented and virtual reality, among others.

This brief provides an overview of the Internet of Things and its applicability in the energy sector, with a focus on how this technology can contribute to increasing shares of VRE in the power system.

The brief is structured as follows:

I Description

II Contribution to power sector transformation

III Key factors to enable deployment

IV Current status and examples of ongoing initiatives

V Implementation requirements: Checklist

I. DESCRIPTION

Our increasingly digitalised world is becoming ever more interconnected. The Internet of Things (IoT) will impact nearly every industry, as machines begin to communicate and make decisions autonomously, without human intervention. Innovations range from smart thermostats maximising energy efficiency by adjusting the temperature of consumers' homes depending on whether they are at home; to refrigerators automatically ordering groceries when food is running low; to sensors on machinery parts that enable data gathering, helping to avoid costly failures by pre-emptively notifying that maintenance will soon be needed.

But what is the IoT? The IoT is the inter-networking[1] of physical devices embedded with electronics, software, sensors and exchange data (also referred to as "connected devices" and "smart devices"). Simply put, the IoT transforms physical objects into smart devices to collect communicate, monitor and interpret information from their surroundings in real time (WCO, 2019). The IoT connects devices through the Internet, where each device has a unique IP address, enabling remote monitoring and control through cloud-based control systems. The goal of the IoT is to increasingly automate aspects of our lives while increasing the efficiency of processes.

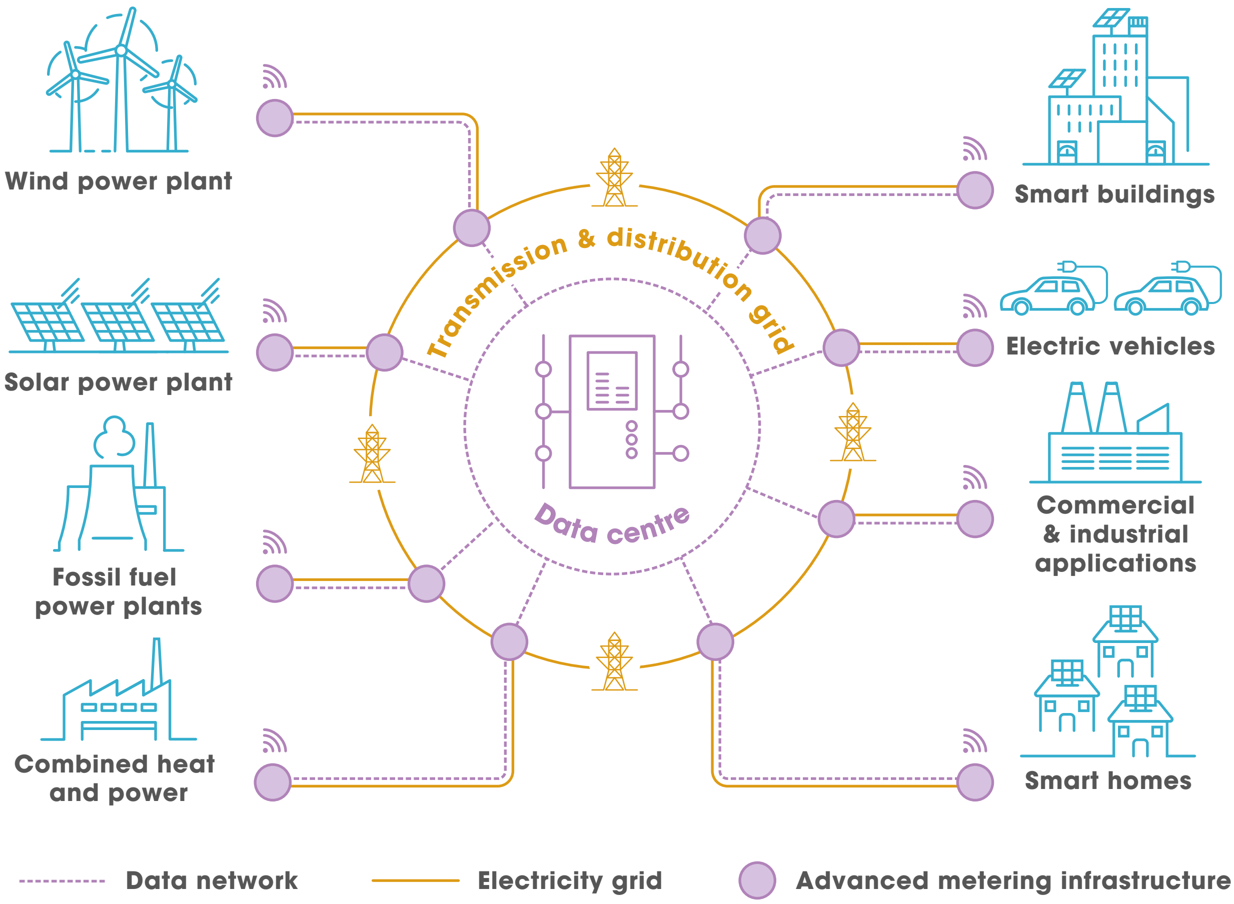
In the power sector, the IoT could play a valuable role in making electricity systems more efficient, or "smart". The IoT is a pillar of "smart grids", which are fundamentally an "electricity network that can intelligently integrate the actions of all users connected to it – generators, consumers and those that do both – in order to efficiently deliver sustainable, economic and secure electricity supplies" (IEC, 2019). Features of smart grids include the rapidly controllable two-way flow of electrical power, the automated, bidirectional flow of information and even automatic system dispatch on an economic basis.

When the decentralisation of the system is considered, through the deployment of distributed energy generation and battery storage, the IoT holds significant potential for new management and business model options due to its capacity to aggregate data. The deployment of distributed energy resources changes a typical power system from having hundreds of control points to potentially millions. Future decentralised systems require micro-level monitoring and control to reach their potential as providers of services to enhance electricity systems operation.

1 Internetworking is the process or technique of connecting different networks by using intermediary devices such as routers or gateway devices. Internetworking ensures data communication among networks owned and operated by different entities using a common data communication and the Internet Routing Protocol.

IoT technology has the potential to increase the flexibility and responsiveness of the smart assets connected to the grid, as well as the visibility of these assets for the system operator. By connecting energy suppliers, consumers and grid infrastructure, IoT technology aims to facilitate the operation of complex systems and to open new commercial possibilities by enabling clients to further monetise the value created by their assets by providing different services through demand-side management.

Figure 2: IoT in context – Smart grids connecting smart devices, from both the demand and supply sides



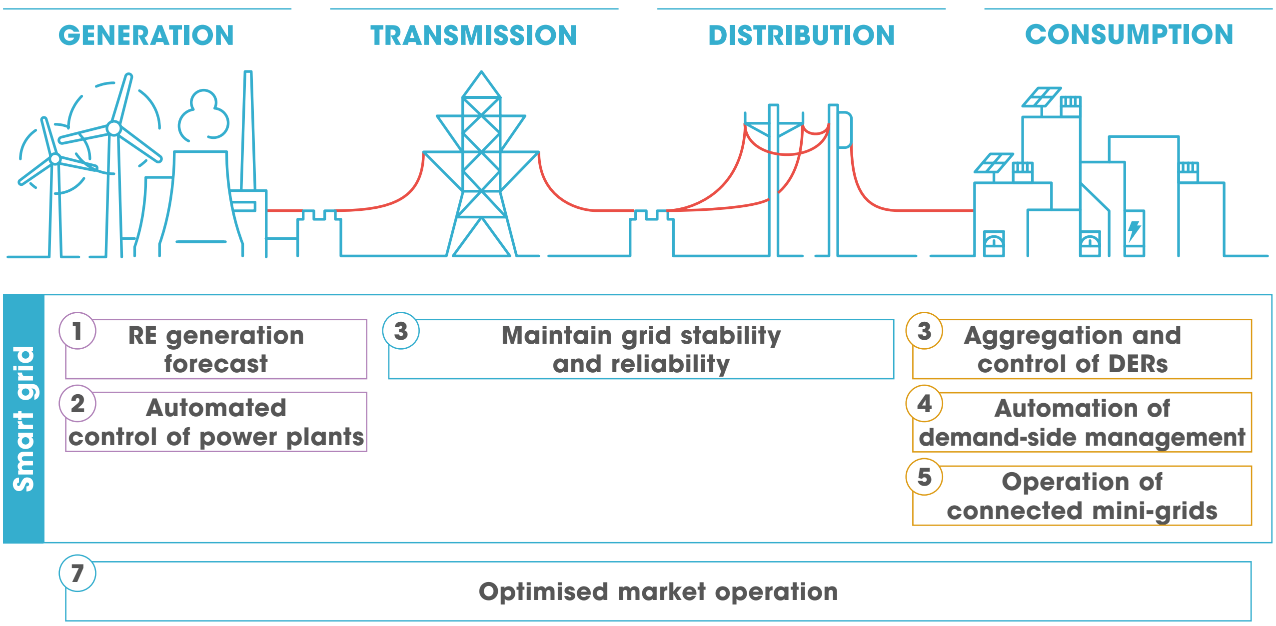
Source: IRENA, adapted from Höfling and Koschel (2019)

II. CONTRIBUTION TO POWER SECTOR TRANSFORMATION

IoT technologies, namely the data that the devices generate and the automated control they provide, are underpinning a historic transformation that will lead to cleaner, more distributed and increasingly intelligent grids. Improved availability of information across the whole value chain enables better decision-support tools (such as artificial intelligence) and enables remote control and automated execution of decisions (*e.g.*, control of millions of devices with immediate actions, such as algorithm trading or self-driving cars). The application of digital monitoring and control technologies in the power generation and transmission domains has been an important trend for several decades, and has recently started penetrating deeper into power systems. The IoT can lead to better management of assets and operations, resulting in greater reliability and enhanced security as well as new services and business models.

This brief focuses on IoT applications that support the integration of high shares of VRE. The disruptive implications of tens of billions of connected sensors and devices sending and receiving vast quantities of granular data across networks are still being studied. Great potential exists, particularly for unlocking greater flexibility in power systems through demand-side management. The IoT also brings solutions to optimise systems on both the supply and demand sides, leading to enormous opportunities for the integration of larger shares of variable renewable generation into the system (see Figure 3).

Figure 3: Current state of digitalisation of the energy value chain



DER = distributed energy resources

Source: IRENA, IRENA, adapted from BNEF, 2017

1. Renewable energy generation forecast

The IoT enables the distribution of computing intelligence throughout the entire power system infrastructure and enables accessing data from remote wind farms, solar farms or hydro stations in real time. Past generation and weather patterns, together with real-time data collected and communicated through digital systems, can help improve the accuracy of renewable generation forecasts. This would enable renewables participation in electricity markets and help operate the system.

Forecast errors in wind generation increase as wind output levels rise, making it more difficult to manage transmission networks. General Electric estimates that by implementing digital systems and data analytics, forecast accuracy can increase up to 94% from around 88% today (for more details see IRENA's brief, *Advanced forecasting of variable renewable power generation* [IRENA, forthcoming]) (GE, 2016). Furthermore, IBM announced at the CES 2019 conference that it aims to use crowdsourced sensor data to improve local weather forecasting globally. By using a Global High-Resolution Atmospheric Forecasting System (GRAF), IBM said it could offer day-ahead forecasts updated hourly on average, with a 3-kilometre resolution. GRAF incorporates IoT data into its weather models via crowdsourcing (Dignan, 2019).

Recently, Tesla, a US company, commissioned the world's largest Li-ion battery storage capacity of 100 MW/ 129 MWh at the 315 MW Hornsdale Wind Farm in South Australia to provide contingency reserves and frequency regulation services to the South Australia grid. A recent report from the Australian Energy Market Operator states that frequency regulation services provided by this project are both rapid and precise, being comparable to services provided by conventional synchronous generation units (AEMO, 2018).

2. Automated control of power plants

The availability of data surrounding all aspects of the electricity supply chain enables system operators to create more precise predictions about a wide variety of factors. Real-time data could complement the current practice of managing energy supply based on historical data. This transition from reactive to proactive operations is one of the defining and most important features of a smart grid and IoT technology, offering better control over operations.

Applications range from embedded sensors in wind turbine vanes that sense changing wind conditions and prompt real-time adjustments of pitch and rotation to maximise efficiency, to substation control systems that can respond rapidly to network disruptions, thus minimising downtime without human intervention. Similarly, light sensors installed in solar panels can indicate the points where the sunlight energy is the highest, while microcontrollers can activate one motor that tilts the panel through an angle of 45° on the vertical axis and a second motor that can rotate the panel through a 360° angle at a point on the horizontal axis.

3. Maintain grid stability and reliability

Digital technologies can assist in maintaining grid stability and reliability, improving system operation. Using the IoT to connect, aggregate and control industrial and residential loads can allow them to participate in frequency regulation markets and provide balancing services to the grid. An intelligent communications network is the foundation of building a smart grid. Also, substation automation can further improve operations, leading the way to entirely autonomous energy grids. This way, the system can respond more effectively to intermittency from industrial-scale renewable plants as well as smaller distributed generation, by using existing resources.

However, the grid must be observable and measurable before it can be controlled and automated. Substation automation helps utilities add protection and control functions while also providing greater visibility into the performance and health of grid infrastructure. System operators are investing in communications networks to improve their situational awareness of grid assets in order to control, automate and integrate systems. Value is created when the peak load demand is "smoothened out", decreasing the use of costly spinning reserves and alleviating the need for long-term investments in new generation plants and other capital investments. Cisco is working on substation automation (Cisco, 2018).

Also, Cisco is working to modernise the power grid with Field Area Network (FAN). FAN aims to help enable pervasive monitoring and control of energy distribution networks to enhance energy delivery. The Cisco multi-service FAN solution is based on a flexible two-tier architecture that generates IP network services such as security, quality of service, resilience and management, supporting use cases such as Advanced Meter Infrastructure (AMI), distribution automation and work force automation (Cisco, *n.d.*).

4. Aggregation and control of distributed energy resources*

Decentralisation of energy systems must be done in co-ordination with their digitalisation. The grid is becoming more complex due to increasing deployment of distributed energy resources, with system operators requiring greater visibility of changing conditions of electricity networks. The transition from one-way power flows to two-way power flows – with intermittent distributed resources such as wind or solar, and behind-the-meter processes such as on-site energy storage or electric vehicle charging to the main grid – requires digital technologies to adapt. Additionally, the electrification of end-use sectors will mean an expected growth in demand arising from the electrification of heat and transport which, without digital demand management technologies, would require large increases in grid capacity. Automated control over distributed energy sources and their aggregation into virtual power plants will support grid operation, by balancing intermittency in the grid and regulating power flows. Digitalisation would enable system operators to alert distributed energy resources to the current needs of the grid, so that consumers, retailers or other service providers could react and benefit accordingly. The IoT can support this process by improving the monitoring of end-devices and data integration into the system. Distribution automation and the IoT are already being introduced into the grid, with aggregators as key emerging players that facilitate distributed energy sources to participate in electricity and ancillary service markets (for more details see the Innovation Landscape brief *Aggregators* [IRENA, 2019c]).

In Belgium, the electricity transmission system operator Elia accepts distributed energy resource capacity to compensate for the mismatches between production and peak power demand. Aggregators, such as REstore and Next Pool, provide the required capacities to Elia from distributed energy resources. With IoT technology, REstore aggregates flexible industrial capacities – 1.7 gigawatts in total – and constantly monitors the grid load. At peak demand moments, companies in REstore's portfolio help to maintain grid balance by load shifting, enabled by automated control. Through digitalisation, Next Kraftwerke is aggregating 5 000 energy-producing and energy-consuming units in the virtual power plant (VPP) Next Pool. With a total capacity of over 4 100 megawatts (not only in Belgium) the VPP trades the aggregated power on different energy spot markets. The VPP contributes substantially to stabilising the grid by smartly distributing the power generated and consumed by the individual units during times of peak load.

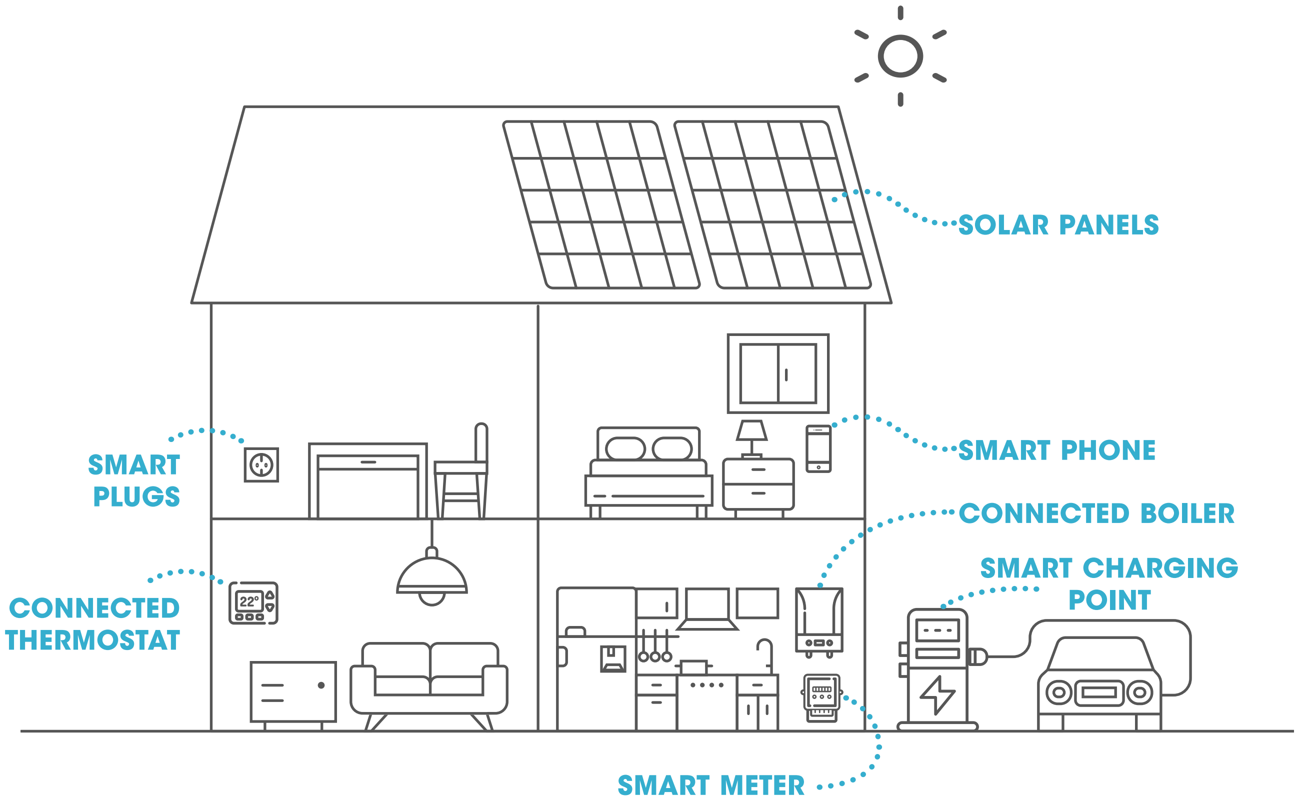
* Distributed energy resources are small or medium-sized resources that are directly connected to the distribution network. They include distributed generation, energy storage (small-scale batteries) and controllable loads, such as electric vehicles, heat pumps and demand response (see the Innovation Landscape brief *Market integration of distributed energy resources* [IRENA, 2019b]).

5. Automation of demand-side management

The IoT enables demand-side management at a micro scale and offers flexibility to the system, provided that time-of-use electricity tariffs are in place to incentivise the consumption of electricity at times when VRE is available. Automation and digitalisation of home appliances, as well as ready-made services for consumers, are key for demand management and demand response.

Thermostats, lighting, and energy monitoring and controls are increasingly embedded with Internet-connected smart devices that can be controlled remotely by smart phones. "Smart appliances" have been available since the 1980s but were "smart" only in the sense that they had computer chips to monitor operations and inform users about issues. Adding communication capabilities and remote controls to existing sensors and diagnostics creates a functioning energy management system. The IoT can turn houses into smart homes and is expected to drive innovation and create new business models for the consumer, such as new forms of demand management and creative alternatives to traditional energy consumption patterns.

Figure 4: IoT and smart homes

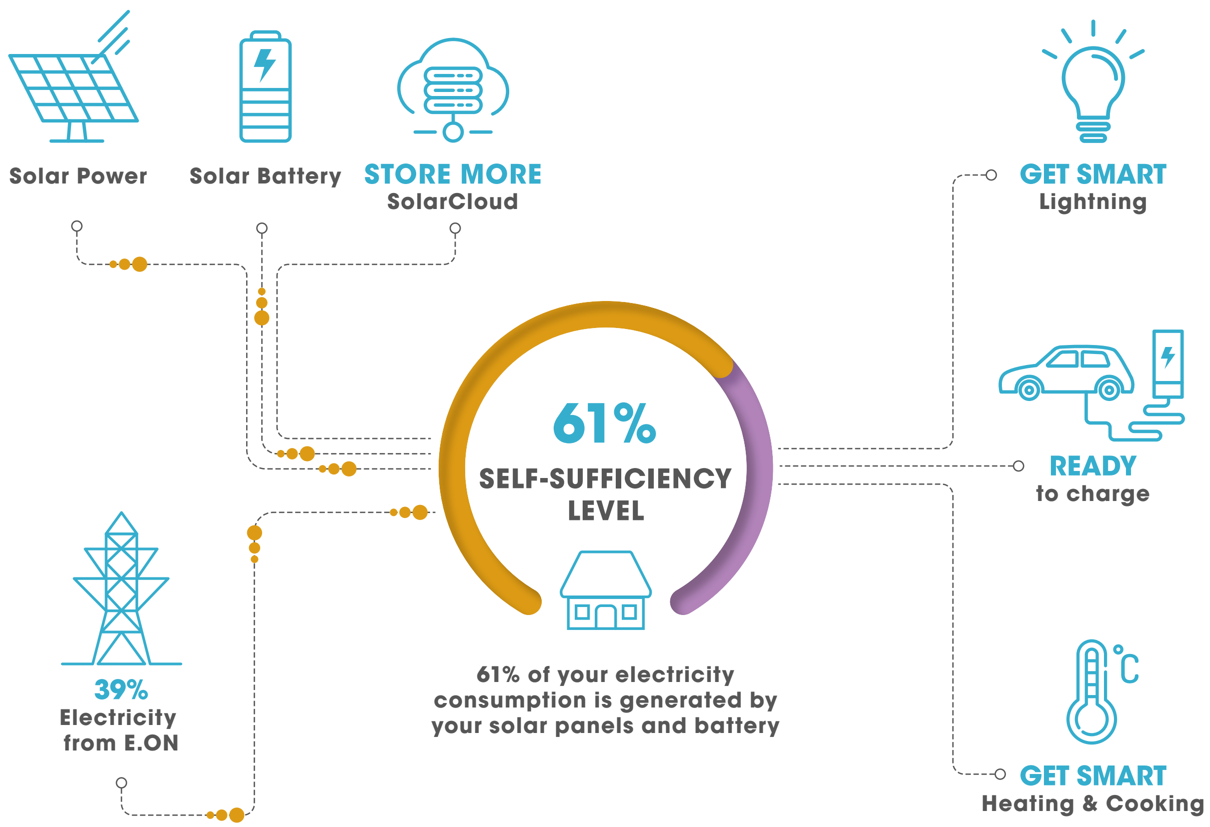


The impacts of digitalised systems in the energy efficiency of buildings are clear. From sensors designed to monitor room temperature to complex applications controlling the energy use of entire buildings, IoT technology is cutting costs and creating more productive, connected buildings. In commercial buildings, connected devices and integrated energy management systems generate data that can be used to reduce heating or cooling in underutilised zones and to adjust lighting when offices or spaces are empty.

Adding artificial intelligence algorithms can increase the energy efficiency even further (see the Innovation Landscape brief *Artificial intelligence and big data* [IRENA, 2019d]). In the United States alone, 30% of the energy used in an average commercial building is wasted, according to the Department of Energy (US DOE, 2019). In Europe, the Stockholm-based telecom company Telia has signed a deal with ONE Nordic AB to connect nearly 1 million electricity meters for Swedish electricity distributor Ellevio. The partnership will rely on Telia's recently launched Narrowband Internet of Things (NB-IoT) network, a low-power, wide-area technology designed to deliver small amounts of IoT data on a massive scale (Telia, 2019).

E.ON, one of Europe's largest energy companies, has partnered with Microsoft to integrate Azure Sphere (an IoT solution that combines secured chips, a unique operating system and cloud services to ensure software updates) into the company's "E.ON Home" solution, to secure the management of demand-side resources (Microsoft, 2018). These devices aim to provide consumers with increased security, visibility and control over their assets, as illustrated in Figure 5.

Figure 5: E.ON Home, secured by Microsoft Azure Sphere technology



Source: Microsoft, 2018

Another example is the Flex PowerPlay, a smart home energy platform launched in 2017 in Australia that consists of three elements: solar panels, a home battery and an IoT monitoring system. The Energy App allows users to simply switch between appliances and automatically control power loads, helping to control energy consumption and related costs. Similar optimisation solutions will be essential for users to reap the benefits of their solar systems and reduce electricity bills. Users can monitor their power generation and manage it in real time via an application on a smart phone. PowerPlay, working with smart technology appliances, can be programmed to turn the lights on in the night and off again during daytime. Users can also remotely control their air conditioners, televisions and sound systems. The platform not only shows the exact amount of real-time energy generation, but also allows consumers to automatically optimise their consumption.

In 2017, SP Group launched the "SP Utilities App", which aims to empower consumers with knowledge and tools so that they can optimise their electricity consumption and decrease costs. Around 25% of households in Singapore have used the app, which allows consumers to monitor their electricity consumption data on a 30-minute interval for those with Advanced Metering Infrastructure (AMI) or smart meters. SP Group also introduced a new feature to help simplify the decision-making processes for consumers faced with myriad choices of retailers and retail plans. The engine matches the consumer's current utility consumption with the retail plans available and recommends plans that result in the best savings for the consumer (Singapore Power, *n.d.*).

6. Operation of connected mini-grids

Microgrids combine power demand with distributed energy resources into a single controllable entity that can be operated separately from the grid. Mini-grids enable renewable energy deployment in grid-connected areas, allowing local generation to provide independence from the main grid at times, and in areas that are not connected to the grid, powering remote communities with distributed generation.

Digital tools allow a mini-grid to automatically deal with the multitude of individual devices, forecast demand and generation, operate the system, optimise reserves, control voltage and frequency, and connect or disconnect from the main grid, when possible. The more effectively these sources are balanced, the lower the generation costs for the mini-grid and the higher the revenue from additional services provided to the main grid. For example, the research institutes CSIRO and the National Renewable Energy Laboratory, from Australia and the US respectively, are working together to simplify the integration of renewable energy mini-grid systems by creating a plug-and-play controller that can maximise the use of solar energy (NREL, 2016; Ritchie, 2013).

New tools, including blockchain paired with smart devices, can facilitate decentralised, peer-to-peer trading in mini-grid systems. These tools can consequently increase transparency, and have the potential to minimise operation costs while offering new revenue streams for prosumers (see the Innovation Landscape brief *Renewable mini-grids* [IRENA, 2019e] and the Innovation Landscape brief *Blockchain* [IRENA, 2019f]).

7. Optimised market operation

A system where energy is traded in shorter increments is more difficult to manage and requires a greater degree of automation. Digital systems can monitor remote generators and automatically send simple instructions, operational data and corrections to operators.

Algorithmic trading, or algo-trading, is an emerging method of electricity trading. Algo-trading is a method of executing a large order (too large to fill all at once) using automated pre-programmed trading instructions, accounting for variables such as time, price and volume to send small slices of the order out to the market over time. These methods have been developed in the financial sector so that traders would not need to constantly watch a stock and execute trades by hand. Currently, more than 50% of the trades conducted on the German intraday market are algo-trades (EPEX Spot, 2018). Enabled by data collection and a communication system with IoT, algorithms are able to fine-tune positions in response to movements in market prices and changing forecasts, at lower cost than employing teams of human traders to operate 24/7.

Other IoT applications in the power sector

Another key benefit of IoT data is in preventive maintenance. Proactive tests and repairs can reduce machine downtime and maintenance costs. This can be applied to generation, transmission and distribution systems, all of which are asset intensive. Smart devices and sensors, for example, can send information from remote equipment indicating an imminent failure, thus avoiding costly downtime or damage. GE's Predix Platform was designed to simplify data collection and forwarding for industrial applications, in order to enable companies to engage in smart predictive maintenance (GE, 2019).

Digital systems are expected to deliver significant operations and maintenance (O&M) savings through practices and systems such as: condition-based maintenance from data and trends gathered; reduction in manpower; minimisation of impact of human errors; improved asset-life management; and optimisation in utilisation of assets. Globally, the International Energy Agency estimates that O&M costs in power generation and electricity networks were just over USD 300 billion in 2016. Through 2040, a 5% reduction in O&M costs achieved through digitalisation could save companies, and ultimately consumers, close to USD 20 billion per year on average (IEA, 2017).

Furthermore, power production can be increased by identifying and addressing causes of inefficiencies, as well as better capturing renewable energy resources, and through significant improvements in long-, mid- and short-term weather prediction (thus minimising the need for operational reserves).

III. KEY FACTORS TO ENABLE DEPLOYMENT

IoT technology still faces several serious challenges that need to be overcome before widespread implementation is possible. The biggest factors include reliability, security and communication.

Technology maturity and reliability

The IoT essentially means letting machines communicate. The fundamentals should be solid and proven before removing human interference, hence high-quality standards for each single implementation are required. This implies a multi-stage approach for implementation: from setting up sensors, data collection, data pre-processing, processing, testing and cyber security risk management, to coping with (new) regulatory policies.

While some consumers already use smart devices such as activity trackers, smart thermostats and drones, industrial IoT requires additional conditions to be met before it becomes widely used. Reliability is one of them. A connectivity failure between a smart thermostat and a boiler at home or between process control sensors in the steel industry have vastly different consequences.

Industrial adoption of IoT technology, including industrial machines, factories and buildings, offers vast opportunities. To increase the use of IoT technology while ensuring reliability, highly qualified software engineers and extensive testing of IoT devices are needed before deployment. Also, a local interface should be available to allow consumers to override systems in case of failure.

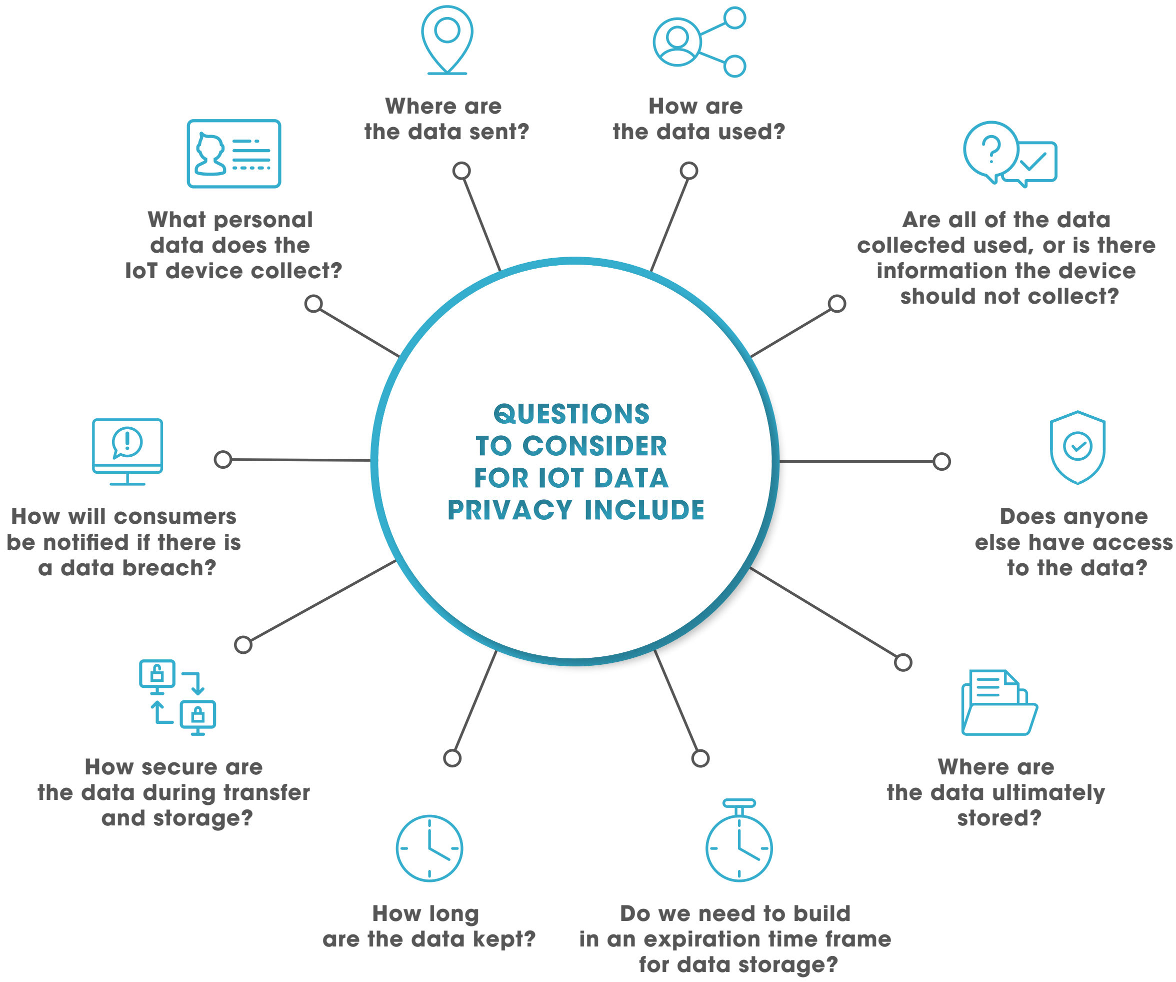
A study from IDC projects that "smart manufacturing" will be the largest potential application for the IoT in the energy sector moving forward (IDC, 2017).

Data privacy

As we progress into an ever more connected, digitalised world, data rights and privacy become increasingly important. Electric vehicles, for instance, could exchange information that might be considered personal, such as detailed information about their location or times of day when they are using energy or being charged. Smart home appliances could collect data on personal habits such as when you are home and when you go to sleep. Privacy has two issues: on the one hand, data might be exploited commercially (legally), and on the other, data might be stolen and exploited illegally. Issues such as secure authentication, standardisation, interoperability and liability need to be properly addressed.

Data ownership, data location and data protection will also require action at the national and international levels. For example, in the European Union (EU), Regulation 2016/679 on the protection of natural persons with regard to the processing of personal data and on the free movement of such data sets strict rules (EC, 2016). When considering data privacy regulations around the world, particularly those required by the EU's General Data Protection Regulations (GDPR), in effect since May 2018, the amount of data generated by the growing IoT is a pressing concern. Both developers and consumers of IoT devices should be aware of the data privacy and security implications (IEEE, 2019).

Figure 6: Questions to consider for IoT data privacy



Adapted from (IEEE, 2019)

Cybersecurity

Security is an important issue that needs to be solved for IoT technologies to be widely deployed. The digitalisation of energy raises several risks and challenges, not the least of which are guaranteeing network neutrality[2], ensuring fair competition, protecting personal privacy, ensuring data security, and thwarting cyber-crime and cyber-terrorism.

As we automate controls and remove humans from the decision-making process, we may introduce the possibility of systemic failure or systemic cybersabotage. The challenge is not only to make systems more secure to prevent unwanted intrusion, but also to make systems more resilient against the inevitable attempts at intrusion that are difficult to prevent. Super systems will be required to monitor and contain the effect of attacks, as well as systems that can be isolated and where no single point of failure (error or sabotage) can bring down the entire energy system.

The increasing number of connected devices (Figure 6) has provided a vast surface area for attacks, as shown recently with the Mirai IoT botnet[3], and others, which exploit IoT devices with weak security. The Mirai botnet, for instance, scanned the Internet for IoT devices with a certain type of processor running a stripped-down version of the Linux operating system. Many of these devices were using their default username-and-password combination, which enabled Mirai to log in and infect it (Cloudflare, 2019). In an effort to combat these types of attacks and ensure the validity of information recorded and transmitted by IoT devices (by making the devices much more

2 Network neutrality is the principle that Internet service providers treat all data on the Internet equally, and not discriminate or charge differently by user, content, website, platform, application, type of attached equipment or method of communication.

3 A botnet is a number of Internet-connected devices, each of which is running one or more bots.

tamper-resistant), Microsoft has introduced the Azure Sphere, a secured microcontroller unit running its own operating system and supported by Microsoft cloud services for periodic updates. The aim is to deliver end-to-end IoT security that responds to emerging threats (Microsoft, 2019).

Communications procedures, standards and protocols

Benefiting from this increase in decentralisation requires the ability of all parties to share data about their consumption/production state and to respond (automatically or not) to price signals. Because these benefits are spread across so many actors, the viability of such a system depends on participants keeping to agreements with each other and being appropriately compensated.

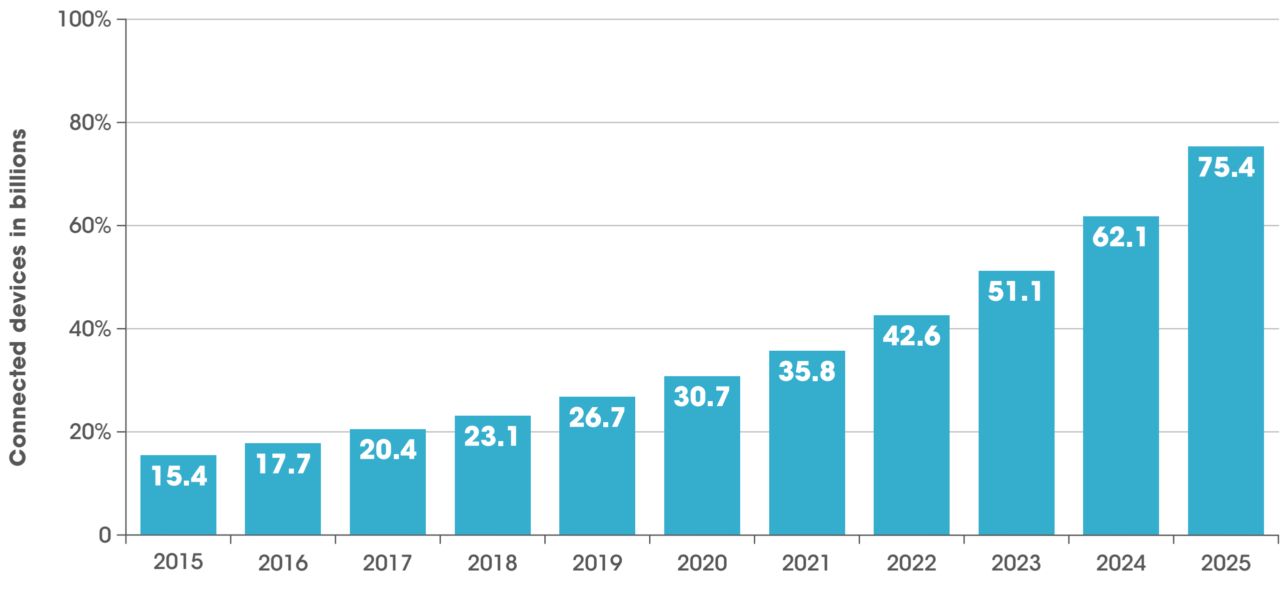
Various means of enabling improved communication between numerous devices and establishing transparent, enforceable contracts exist. Solutions based on blockchain are one example. With their ability to support payments and smart contracts, blockchain applications can accelerate the development of IoT use cases in the energy sector (see the Innovation Landscape brief *Blockchain* [IRENA, 2019f]).

Communications protocols and standards need to be developed to ensure smooth communication between disparate devices. As an example, devices today rely on NFC, Wi-Fi, Zigbee, Bluetooth, DigiMesh and Thread, among many others, but clear means of continuously linking data from various devices are lacking (Postscapes, 2019). Alliances and organisations are working to address the issue of communication through the establishment of IoT protocols.

IV. CURRENT STATUS AND EXAMPLES OF ONGOING INITIATIVES

By 2025, 75 billion devices worldwide are expected to be Internet connected, providing a wealth of information to consumers, manufacturers and utility providers (Statista, 2018). The rise of the IoT goes hand in hand with the rise of artificial intelligence, powered by big data, as it provides the granular information needed to feed machine learning algorithms (see the Innovation Landscape brief *Artificial intelligence and big data* [IRENA, 2019d]). The explosion of data generated, due in part to the proliferation of IoT devices, will power new technologies and unlock new industries in the coming years and decades.

Figure 7: IoT installed base of connected devices worldwide from 2015 to 2025 (in billions)



Source: Statista, 2018

General Electric estimates that by implementing digital systems and data analytics, renewable energy O&M costs can be reduced by 10%, generation increased by 8% and curtailment cut by 25%. Machine learning algorithms applied to weather and power plant output data can increase the accuracy of forecasts to up to 94%, from around 88% across the industry (GE, 2016; GE, 2017).

Most importantly, complex systems have the most to gain from IoT integration, where many actors and devices are participating in the power system by injecting or withdrawing power from the grid. To address the full potential of the IoT for smart energy, the ultimate goal is to transform the system into a customer-centric system that can offer more value-added services to the end-consumers. A large number of companies, consortiums, foundations and groups are working on IoT technologies at different levels: the app layer, data layer, connectivity layer and device layer. Table 1 presents a non-exhaustive sampling of major players in the IoT value chain.

Table 1 Major players in the IoT value chain

App layer	**Technology leaders:** Amazon, Apple, Cisco, GE, Google, IBM, Microsoft
	New entrants: Alibaba, Huawei, Samsung, Schneider, Siemens, Tencent
Data layer	**Technology leaders:** AWS, Google Cloud Services, Infosys, Fortinet, IBM, Microsoft, Oracle, SAS, Tableau
	New entrants: Alteryx, Cloudera, Hortonworks, Dataiku, RapidMiner
Connectivity layer	**Technology leaders:** Nokia, Arista Networks, AT&T, Cisco, Dell, NTT, Ericsson, Orange
	New entrants: Citrix, Coriant, Equinix, Bharti Airtel, China Telecom, Tata Comms
Device layer	**Technology leaders:** AMD, Intel, Nvidia, Apple, Fitbit, Honeywell, Sony
	New entrants: AAC Tech, Garmin, GoPro, LinkLabs, Ambarella, Goertek, HTC

Table 2 provides a non-exhaustive sampling of companies, consortiums and foundations working at the intersection of IoT and the power sector, particularly related to VRE integration. A large share of the use cases noted in the table fall within *automation of demand-side management* due to the increasing decentralisation, leading to self-consumption and opportunities for increased energy efficiency on the consumer side.

Table 2 Companies, consortiums and foundations working on IoT in the power sector

Project (company)	Service provided	Description
AMD IoT Gateway (AMD)	• Automation of demand-side management	Provides processors for various applications such as industrial automation.
AMMP	• Operation of connected mini-grids	Enables the monitoring of data of mini-grids on the production side, as well as on the battery and PV inverters using local communication gateways to operate off-grid networks in remote areas.
Analytics for IoT (SAS)	• Maintain grid stability and reliability • Aggregation and control of distributed energy resource assets	Data analytics solution that provides artificial intelligence, machine learning and streaming capabilities to organise and analyse large amounts of data for grid operation and energy systems.

Project (company)	Service provided	Description
AT&T IoT Platform (AT&T)	• Automation of demand-side management	Customisable platform with extensive solution templates that allows the user to integrate data services, devices and automation along with SIM-card connectivity. It can increase energy efficiency and improve energy management in buildings.
Autonomous Energy Grids (NREL)	• Aggregation and control of distributed energy resource assets • Maintain grid stability and reliability • Automated demand-side management	NREL is working on an autonomous energy grid that can automate most operations of a smart grid, including transmission and distribution control, energy consumption management and aggregation of distributed energy resource assets such as rooftop PV.
AWS (Amazon)	• Renewable energy generation forecast • Maintain grid stability and reliability • Automation of demand-side management • Automated control of power plants	Provides computation and storage cloud-based capacity for intensive workloads such as weather forecasting and demand response, as well as energy consumption analytics in industrial and residential buildings to improve energy efficiency.
Azure (Microsoft)	• Renewable power generation forecast • Aggregation and control of distributed energy resource assets	Cloud computing service that allows connection, monitoring and management of IoT devices. Combined with ADAMA, it can help to predict solar power production and manage distributed energy resource assets.
Cloud IoT (Google)	• Optimised market operation	Software and cloud platform that connects, processes, stores and analyses data with machine learning capabilities. Can be used for smart billing for smart grid operators and end-users for flexible pricing schemes.
Cloud IoT Hub (Tencent)	• Automated control of power plants • Automation of demand-side management	Platform access service for energy equipment monitoring, energy scheduling and big data processing. Can also be used for smart home management to improve domestic energy efficiency.
EcoStruxure Power (Schneider)	• Automation of demand-side management	Provides actionable data to aid decisions regarding low and medium power distribution systems in buildings.
Enerlytics (Uniper)	• Automated control of power plants	Power plant monitoring platform that enables the optimisation of plant assets, maintenance scheduling and increased efficiency through real-time data streaming and analytics.
FAN (Cisco)	• Maintain grid stability and reliability	Automates distribution services for the enabling of monitoring and control of energy networks.
GRAF (IBM)	• Renewable energy generation forecast	Crowd-sources weather forecasting data from millions of sources to create accurate forecasts for weather conditions and renewable energy generation.
HomeKit (Apple)	• Automation of demand-side management	App provides a simple way for users to connect various home accessories, control them and communicate with them. Can be used with energy management devices to improve energy efficiency in homes.
Hortonworks Dataflow (Hortonworks)	• Maintain grid stability and reliability	Manages streaming data from enterprise operations and assets for predictive analytics and data flow streamlining. Can be used in conjunction with other technologies to monitor transmission lines and smart meters to predict and prevent failures.

Project (company)	Service provided	Description
IMPACT (Nokia)	• Automation of demand-side management	Platform to manage data and devices across endpoints and gain insights using data analytics. Can be used with the Smart Building Energy Management application to improve energy efficiency by offering more data insights and control.
IMRS (Intel)	• Automation of demand-side management • Maintain grid stability and reliability	Uses data to deliver insights on various applications. In the case of smart cities, it can facilitate energy efficiency measures and energy data communication with operators.
IoT Smart Lighting (Tata Communications)	• Automation of demand-side management	Utilises LPWA communications to connect sensors to automate lighting in buildings and public areas for improved energy efficiency and to identify electricity theft locations.
NarrowBand-IoT (Telia)	• Automation of demand-side management • Maintain grid stability and reliability	Provides connectivity between LPWA devices to improve energy efficiency and power consumption, as well as share and visualise data.
Nest Learning Thermostat (Google)	• Automation of demand-side management	Uses machine learning and artificial intelligence to optimise cooling and heating of homes and businesses, which can improve energy efficiency.
PLC-IoT AMI Meter Reading (Huawei)	• Automation of demand-side management • Maintain grid stability and reliability	Provides communication channels for smart meters and displays consumption data for household users and operators.
Predix (GE)	• Automation of demand-side management • Automated control of power plants	Platform for industrial applications that can provide asset connectivity, analytics, machine learning and big data processing, for example for wind farm monitoring.
SolarEdge	• Automated demand-side management • Aggregation and control of distributed energy resource assets	Bundled device solution that provides greater control for residential rooftop PV systems by using smart inverters, storage power optimisers, and monitoring platforms to maximise energy self-consumption, production and safety. It can also be connected to home appliances to increase energy efficiency and reduce electricity bills.
Substation Automation (Cisco)	• Maintain grid stability and reliability	Provides a solution for the automation of substations in areas of predictive maintenance, protection and remote diagnostics.
Tableau	• Automation of demand-side management	Uses data analytics and visualisation for energy consumption and weather forecasts to regulate and manage energy use.

Table data sourced from individual websites.

V. IMPLEMENTATION REQUIREMENTS: CHECKLIST

TECHNICAL REQUIREMENTS	**Hardware:** • Smart meters with high-resolution metering data and sensors. • Sensors installed in different devices. • Supercomputers or "cloud technology". • Other digital technologies add automated control to the electricity system to increase flexibility and manage multiple sources of energy flowing to the grid from local energy resources.
	Software: • Data collection, data pre-processing, processing, testing. • Optimisation tools. • Software for version control, data storage and data quality assessment.
	Communication protocol: • Common interoperable standards (at both the physical and the information and communication technology (ICT) layers). • Define cybersecurity protocols
POLICIES NEEDED	• Inform and empower consumers, including prosumers, to participate in demand-side management programmes. • Encourage data exchange and improved communications on a transparent basis. • Establishment of regulatory sandboxes to try out new business models. • Develop data privacy policy and regulation for consumers and define cybersecurity protocols.
REGULATORY REQUIREMENTS	**Retail market:** • Customer support and empowerment, through efficient price signals, such as time-of-use tariffs, or other load management schemes. • A free retail market that enables innovative business models for consumers, such as energy-as-a-service models.
	Distribution: • Incentivise distribution system operators to invest in smart grids.
	Wholesale market: • Appropriate markets and product-service definitions to value flexibility in operation of generation fleet (and demand response, batteries, etc.).
STAKEHOLDER ROLES AND RESPONSIBILITIES	• **System operators:** Adopt an innovative approach to system operation by enhancing co-operation among distribution and transmission system operators, accounting for the evolving role of distribution system operators. • **Distributed energy resource owners/operators** (*e.g.*, aggregators)**:** Participate in pilot projects as data providers. • **ICT companies:** Work closely with power sector actors (*e.g.*, system operators) to develop tailored digital solutions for smart homes and the integration of VRE into the power system.

ANNEX

Table A1 Organisations working on IoT standards and protocols

ETSI (European Telecommunications Standards Institute) • Connecting Things Cluster
IETF (Internet Engineering Task Force) • CoRE working group (Constrained RESTful Environments) • 6lowpan working group (Ipv6 over Low power WPAN) • ROLL working group (Routing Over Low power and Lossy networks)
IEEE (Institute of Electrical and Electronics Engineers) • IoT "Innovation Space"
OMG (Object Management Group) • Data Distribution Service Portal
OASIS (Organization for the Advancement of Structured Information Standards) • MQTT Technical Committee
OGC (Open Geospatial Consortium) • Sensor Web for IoT Standards Working Group
IoT-A (Internet of Things Architecture) • European Lighthouse Integrated Project addressing IoT architecture, proposing the creation of an architectural reference model and defining an initial set of key building blocks
oneM2M • Aims to develop technical specifications for a common M2M Service Layer that can be readily embedded within hardware and software, and relied upon to connect devices in the field with M2M application servers worldwide.
OSIoT (Open Source Internet of Things) • Developing and promoting royalty-free, open-source standards for the emerging IoT
IoT-GSI (Global Standards Initiative on Internet of Things) • Aimed to promote a unified approach for development of technical standards
ISA (International Society of Automation) • Develops standards, certifies industry professionals, provides education and training, publishes books and technical articles, and hosts conferences and exhibitions for automation professionals
W3C (World Wide Web Consortium) • Semantic Sensor Net Ontology • Web of Things Community Group
EPC Global • Set up to achieve worldwide adoption and standardisation of Electronic Product Code technology.
JTC (Joint Technical Committee) webpage for the **IEC** (International Electrotechnical Commission) and **ISO** (International Organization for Standardization)

Source: Postscapes, 2019

ACRONYMS AND ABBREVIATIONS

AMI	Advanced metering infrastructure
CSIRO	Commonwealth Scientific and Industrial Research Organisation
DER	Distributed energy resources
DLT	Distributed ledger technologies
EU	European Union
FAN	Field Area Network
GDPR	General Data Protection Regulations
GRAF	Global High-Resolution Atmospheric Forecasting System
ICT	Information and communications technology
IoT	Internet of Things
LPWA	Low-power wide-area
LPWAN	Low-power wide-area network
M2M	Machine to machine
NREL	National Renewable Energy Laboratory
O&M	Operations and maintenance
PV	Photovoltaic
US	United States
VPP	Virtual power plant
VRE	Variable renewable energy
WPAN	Wireless personal area network

BIBLIOGRAPHY

Al-Ali, A.R. (2016), "Internet of Things role in the renewable energy resources", Energy Procedia, vol. 100: 34–38, www.sciencedirect.com/science/article/pii/S1876610216311055. Barcelona Digital City (*n.d.*), https://ajuntament.barcelona.cat/digital/en.

Benoit, J. (2016), *The Internet of Things and the energy sector: Myth or opportunity, Eaton's Cooper Power Systems*, www.eaton.com/content/dam/eaton/markets/utility/knowledge-center/white-papers/IoT-and-energy-myth-or-opportunity.pdf.

BNEF (2017), *Digitalization of energy systems – A white paper*, Bloomberg New Energy Finance, London, https://new.siemens.com/global/en/company/topic-areas/sustainable-energy/digitalization-of-energy-systems.html.

Center for Strategic Research North-West (2016, 18 January), "Internet of things changes energy sector", www.csr-nw.ru/en/news1/iot_changes_energy_sector.

Cisco (*n.d.*), "Field Area Network", www.cisco.com/c/en/us/solutions/industries/energy/external-utilities-smart-grid/field-area-network.html.

Cisco (2018), "Substation automation", www.cisco.com/c/dam/en_us/solutions/industries/resources/energy/utlilities/1584310_AAG_Utilities_SubstationAutomation_corpedit.pdf.

Cloudflare (2019), "What is the Mirai Botnet?", Cloudflare Inc., https://www.cloudflare.com/learning/ddos/glossary/mirai-botnet/.

Dignan, L. (2019, 8 January), "IBM aims to use crowdsourced sensor data to improve local weather forecasting globally", ZDNet, https://www.zdnet.com/article/ibm-aims-to-use-crowdsourced-sensor-data-to-improve-local-weather-forecasting-globally/.

EC (2016), *Commission staff working document – Advancing the Internet of Things in Europe*, European Commission, Brussels, https://eur-lex.europa.eu/legal-content/EN/TXT/PDF/?uri=CELEX:52016SC0110&from=EN.

EnergyDigital (2016), "5 Ways the Internet of Things will improve the energy sector", www.energydigital.com/renewable-energy/5-ways-internet-things-will-improve-energy-sector.

EPEX Spot (2018), *Facts and figures*, www.epexspot.com/document/38585/Epex_factsheet_180125_Web.pdf.

GE (2019), "Predix platform", General Electric, https://www.ge.com/digital/iiot-platform.

GE (2017), *Electricity Value Network: Digital solutions for power & utilities*, General Electric, www.ge.com/digital/sites/default/files/download_assets/EVN-Solutions-for-Power-and-Utilities-from-GE-Digital.pdf.

GE (2016), *Digital wind business optimization from GE Renewable Energy: Leveraging sophisticated analytics to drive increased revenue*, General Electric, www.ge.com/digital/sites/default/files/download_assets/GE-Digital-Wind-Business-Optimization-Brochure.pdf.

GlobalData (2018), *Internet of Things in utilities – Thematic research*, GlobalData, London, www.globaldata.com/store/report/gdpe-tr-s005--internet-of-things-in-utilities-thematic-research/.

Höfling, H. and H. Koschel (2019), "Renewable energy: Smart grids", KfW Group, www.kfw.de/stories/kfw/stories/environment/renewable-energy/smart-grids-intelligentes-stromnetz/.

IDC (2017), *Worldwide Internet of Things spending guide*, International Data Corporation, Framingham, Massachusetts, US, www.idc.com/getdoc.jsp?containerId=IDC_P29475.

IEA (2017), *Digitalization & energy*, International Energy Agency, Paris, www.iea.org/publications/freepublications/publication/DigitalizationandEnergy3.pdf.

IEC (2019), "What is a smart grid?", International Electrotechnical Commission, www.iec.ch/smartgrid/background/explained.htm.

IEEE (2019), "IoT and data privacy", Institute of Electrical and Electronics Engineers, innovationatwork.ieee.org/iot-data-privacy/.

IRENA (2019a), *Innovation landscape for a renewable-powered future: Solutions to integrate variable renewables*, International Renewable Energy Agency, Abu Dhabi, https://irena.org/-/media/Files/IRENA/Agency/Publication/2019/Feb/IRENA_Innovation_Landscape_2019_report.pdf.

IRENA (2019b), the Innovation Landscape brief *Market integration of distributed energy resources*, International Renewable Energy Agency, Abu Dhabi.

IRENA (2019c), the Innovation Landscape brief *Aggregators*, International Renewable Energy Agency, Abu Dhabi

IRENA (2019d), the Innovation Landscape brief *Artificial intelligence and big data*, International Renewable Energy Agency, Abu Dhabi.

IRENA (2019e), *Innovation landscape brief: Renewable mini-grids*, International Renewable Energy Agency, Abu Dhabi.

IRENA (2019f), the Innovation Landscape brief *Blockchain*, International Renewable Energy Agency, Abu Dhabi.

IRENA (forthcoming), *Advanced forecasting of variable renewable power generation*, International Renewable Energy Agency, Abu Dhabi.

Lontoh, S. (2016). "What does the internet of things mean for the energy sector?" World Economic Forum, www.weforum.org/agenda/2016/06/what-does-the-internet-of-things-mean-for-the-energy-sector/.

Microsoft (2019), "Azure Sphere", Microsoft Azure, https://azure.microsoft.com/en-us/services/azure-sphere/.

Microsoft (2018), "E.ON and Azure Sphere: Building smart home experiences on a foundation of security", https://blogs.microsoft.com/iot/2018/09/24/e-on-and-azure-sphere-building-smart-home-experiences-on-a-foundation-of-security/.

Monnier, O. (2013), *A smarter grid with the Internet of Things*, Texas Instruments, Dallas, Texas, US, http://www.ti.com/lit/ml/slyb214/slyb214.pdf?DCMP=iotweek&HQS=gma-indu-gsg-mtrg-iotweek-otgrid-20140508-mc-en.

Nivas, H. (2016), "IoT in renewable energy: Energy meets Internet of Things", DZone, https://dzone.com/articles/iot-in-renewable-energy-energy-meets-internet-of-t.

NREL (2016), "Energy systems integration", US National Renewable Energy Laboratory, Golden, Colorado, US, https://www.nrel.gov/docs/fy17osti/65036.pdf.

Postscapes (2019), "IoT standards and protocols", https://www.postscapes.com/internet-of-things-protocols/.

Rifkin, J. (2015), *The German Energy Transition: The Internet of Things, zero marginal cost renewable energy and the Third Industrial Revolution*, Bethesda, Maryland, US, https://www.bee-ev.de/fileadmin/Publikationen/Sonstiges/3_19_2015_Digital_Germany_For_March_26th_German_Energy_Transition_Dialogue_Event.pdf.

Ritchie, T. (2013, 22 March), "The hot new product for grids: Plug and play solar", RenewEconomy, https://reneweconomy.com.au/the-hot-new-product-for-grids-plug-and-play-solar-55331/.

Schulz, Y. (2015, 13 November), "6 ways IoT enables innovation in the energy industry", IT World Canada, https://www.itworldcanada.com/blog/6-ways-iot-enables-innovation-in-the-energy-industry/378329.

Singapore Power (*n.d.*)

Statista (2018), "Internet of Things (IoT) connected devices installed base worldwide from 2015 to 2025 (in billions)", https://www.statista.com/statistics/471264/iot-number-of-connected-devices-worldwide/.

Strother, N. (2016, 12 December), "The Internet of Things is an enormous opportunity for renewable energy", REcharge News, http://www.rechargenews.com/solar/1198631/the-internet-of-things-is-an-enormous-opportunity-for-renewable-energy.

Telia (2019, 24 April), "Telia to connect close to one million NB-IoT electricity meters for One Nordic", Telia Company, https://www.teliacompany.com/en/news/news-articles/2019/telia-to-connect-close-to-one-million-nb-iot-electricity-meters-for-one-nordic/.

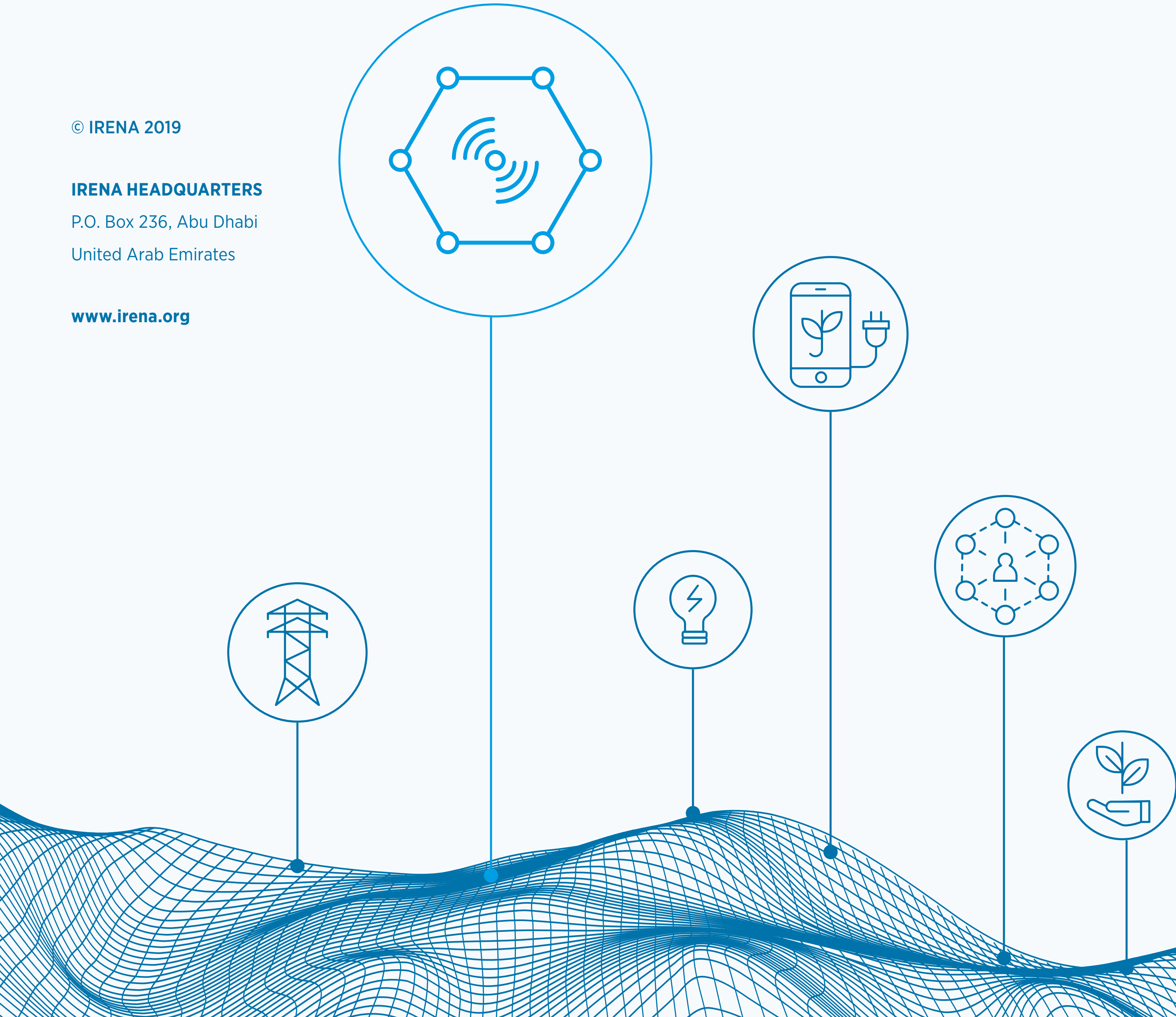
US DOE (2019), "About the Commercial Buildings Integration Program", US Department of Energy, Office of Energy Efficiency and Renewable Energy, https://www.energy.gov/eere/buildings/about-commercial-buildings-integration-program.

WCO (2019), *Study report on disruptive technologies*, World Customs Organization, Brussels, http://www.wcoomd.org/-/media/wco/public/global/pdf/topics/facilitation/instruments-and-tools/tools/disruptive-technologies/wco_disruptive_technologies_en.pdf?la=en.

Young, R., J. McCue and C. Grant (2016, 21 January), "The power is on: How IoT technology is driving energy innovation", Deloitte Insights, https://www2.deloitte.com/insights/us/en/focus/internet-of-things/iot-in-electric-power-industry.html.

IRENA
International Renewable Energy Agency

INTERNET OF THINGS
INNOVATION LANDSCAPE BRIEF



IRENA HEADQUARTERS
P.O. Box 236, Abu Dhabi
United Arab Emirates

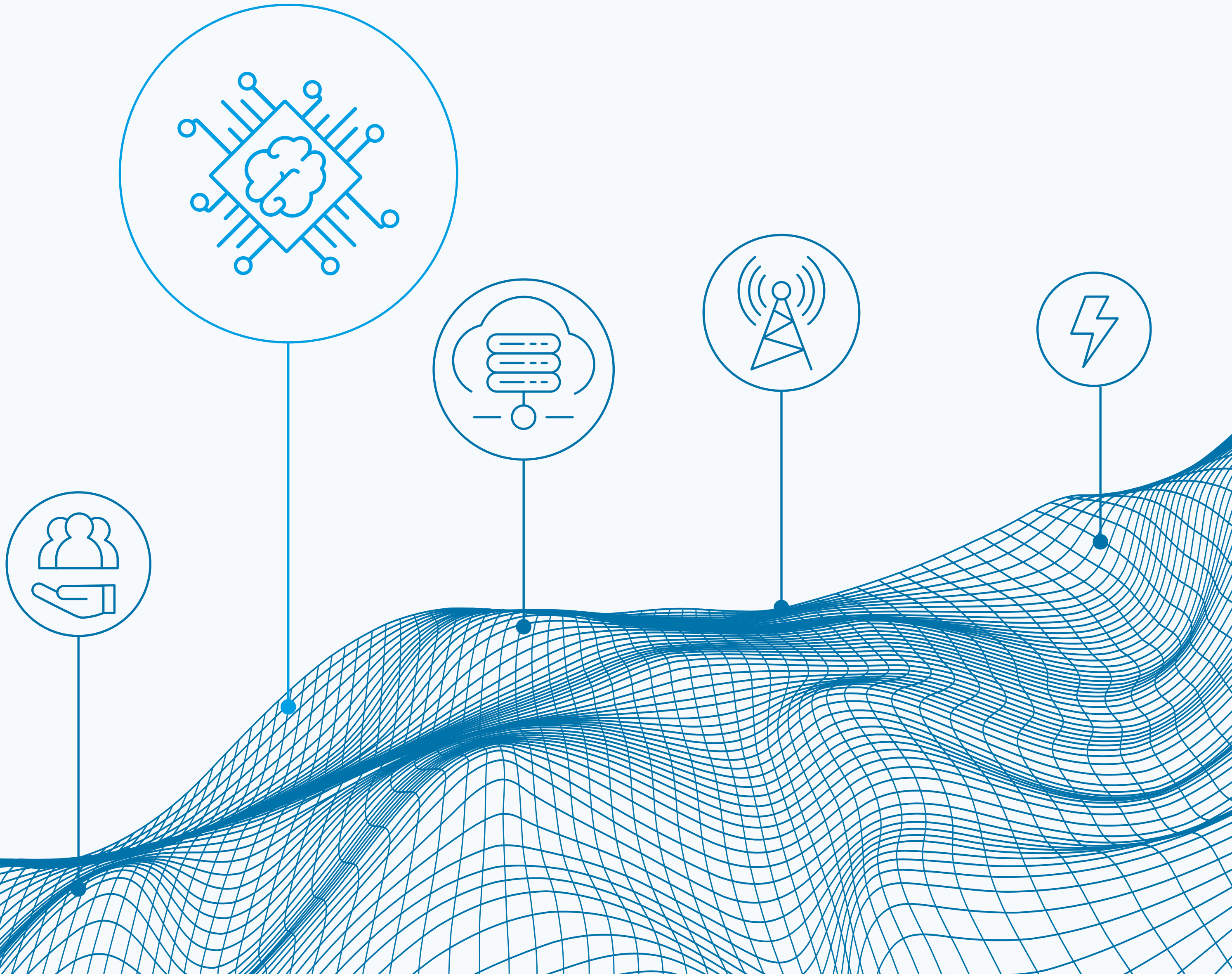
www.irena.org

IRENA

International Renewable Energy Agency

ARTIFICIAL INTELLIGENCE AND BIG DATA

INNOVATION LANDSCAPE BRIEF



ISBN 978-92-9260-143-0

Citation: IRENA (2019), *Innovation landscape brief: Artificial intelligence and big data*, International Renewable Energy Agency, Abu Dhabi.

ACKNOWLEDGEMENTS

This report was prepared by the Innovation team at IRENA's Innovation and Technology Centre (IITC) with text authored by Sean Ratka, Arina Anisie, Francisco Boshell and Elena Ocenic.

This report benefited from the input and review of experts: Mark Peters (IBM), Neil Hughes (EPRI), Stephen Marland (National Grid), Stephen Woodhouse (Pöyry), Luiz Barroso (PSR) and Dongxia Zhang (SGCC), along with Emanuele Taibi, Nadeem Goussous and Paul Komor (IRENA).

Report available online: www.irena.org/publications
For questions or to provide feedback: publications@irena.org

www.irena.org

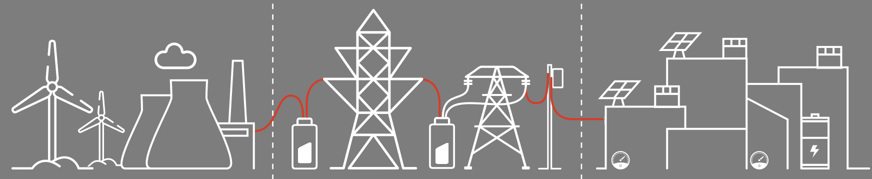
IRENA
International Renewable Energy Agency

1 BENEFITS

AI potential is being unlocked by the generation of big data and increased processing power.

In the energy sector, AI can enable fast and intelligent decision making, leading to increased grid flexibility and integration of VRE.

AI applications for wind and solar integration



- Wind and solar generation forecast
- Grid stability and reliability
- Demand forecast
- Demand-side management
- Optimised energy storage operation
- Optimised market design and operation

2 KEY ENABLING FACTORS

- Technological maturity
- Availability and quality of data
- Growing importance of cybersecurity
- Training and re-skilling of energy sector professionals

3 SNAPSHOT

- EWeLiNE and Gridcast in Germany use AI to better forecast solar and wind generation, minimising curtailments.
- DeepMind AI has reduced cooling consumption at a Google data centre by 40%. It applies machine learning to increase the centre's energy efficiency.
- EUPHEMIA, an AI-based coupling algorithm, integrates 25 European day-ahead energy markets to determine spot prices and volumes.

WHAT IS ARTIFICIAL INTELLIGENCE?

Intelligent machines work and react more like humans.
Artificial intelligence (AI) systems can change their own behaviour without explicit re-programming.
They do so by collecting and analysing large datasets, or "big data".

ARTIFICIAL INTELLIGENCE AND BIG DATA

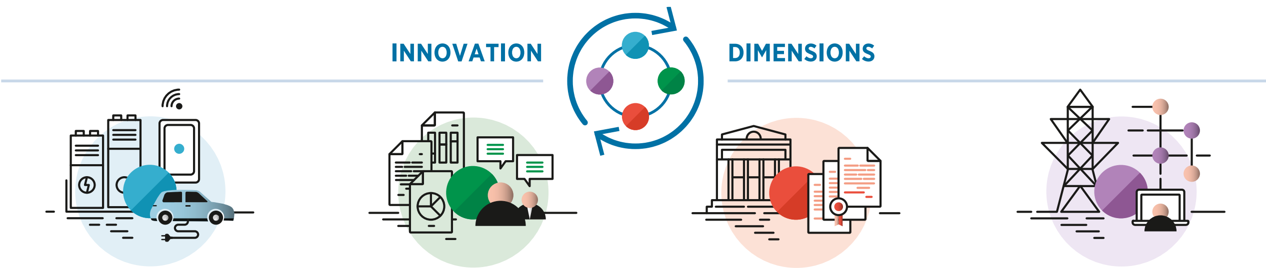
Intelligent tools help manage **complex power systems** and extract value from **new data.**
AI supports the **decision-making process.** Big data provides a **clear overview, input for AI.**

ABOUT THIS BRIEF

This brief is part of the IRENA project "Innovation landscape for a renewable-powered future", which maps the relevant innovations, identifies the synergies and formulates solutions for integrating high shares of variable renewable energy (VRE) into power systems.

The synthesis report, *Innovation landscape for a renewable-powered future: Solutions to integrate variable renewables* (IRENA, 2019a), illustrates the need for synergies among different innovations to create actual solutions. Solutions to drive the uptake of solar and wind power span four broad dimensions of innovation: enabling technologies, business models, market design and system operation.

Along with the synthesis report, the project includes a series of briefs, each covering one of 30 key innovations identified across those four dimensions. The 30 innovations are listed in the figure below.



ENABLING TECHNOLOGIES

1 Utility scale batteries
2 Behind-the-meter batteries

3 Electric-vehicle smart charging
4 Renewable power-to-heat
5 Renewable power-to-hydrogen

6 Internet of Things
7 Artificial intelligence and big data
8 Blockchain

9 Renewable mini-grids
10 Supergrids

11 Flexibility in conventional power plants

BUSINESS MODELS

12 Aggregators
13 Peer-to-peer electricity trading
14 Energy-as-a-service

15 Community-ownership models
16 Pay-as-you-go models

MARKET DESIGN

17 Increasing time granularity in electricity markets
18 Increasing space granularity in electricity markets
19 Innovative ancillary services
20 Re-designing capacity markets
21 Regional markets

22 Time-of-use tariffs
23 Market integration of distributed energy resources
24 Net billing schemes

SYSTEM OPERATION

25 Future role of distribution system operators
26 Co-operation between transmission and distribution system operators

27 Advanced forecasting of variable renewable power generation
28 Innovative operation of pumped hydropower storage

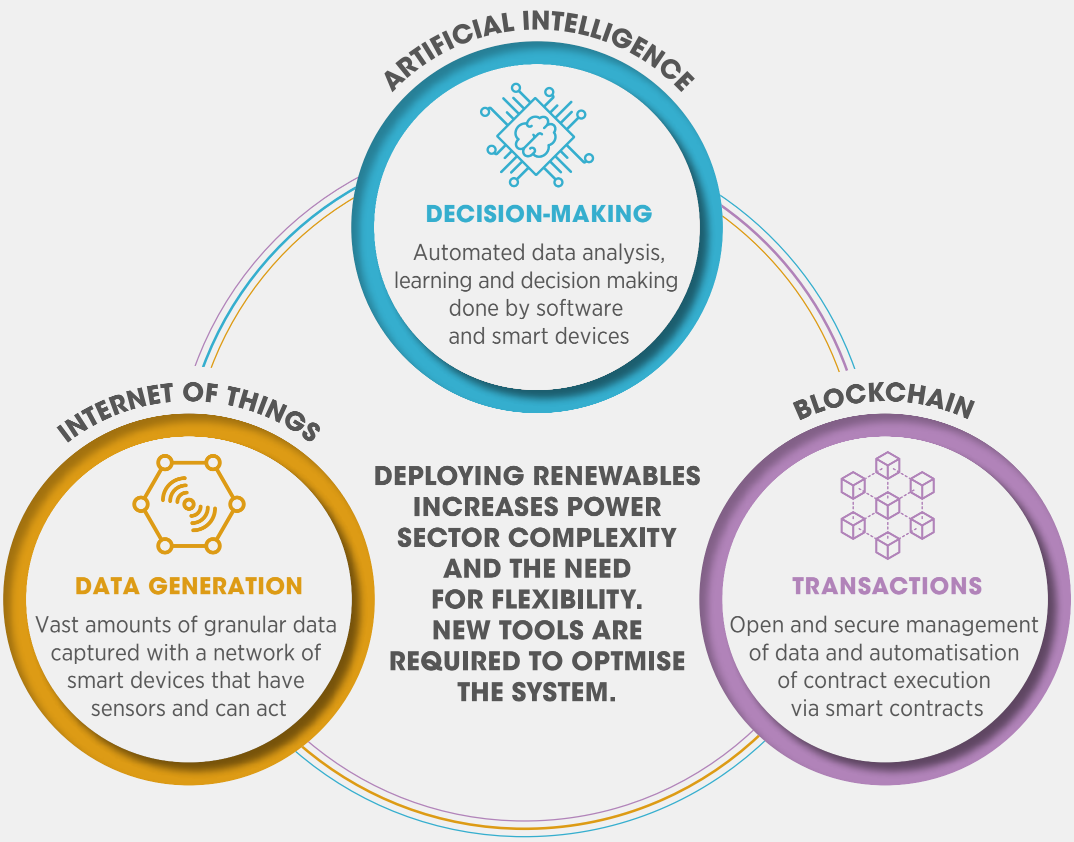
29 Virtual power lines
30 Dynamic line rating

Digitalisation to support VRE integration

Digitalisation is a key amplifier of the power sector transformation, enabling the management of large amounts of data and optimising increasingly complex systems. For the power sector, digitalisation is essentially converting data into value (IRENA, 2019a). The growing importance of digitalisation in the power sector is also a consequence of advances in two other innovation trends: decentralisation and electrification. Decentralisation is led by the increased deployment of small power generators, mainly rooftop solar photovoltaic (PV), connected to the distribution grid. Electrification of transport and buildings (heating and cooling) involves large quantities of new loads, such as electric vehicles, heat pumps and electric boilers. All these new assets on the supply and demand sides are adding complexity to the power sector, making monitoring, management and control crucial for the success of the energy transformation.

Digital technologies[1] can support the renewable energy sector in several ways, including better monitoring, operation and maintenance of renewable energy assets; more refined system operations and control closer to real time; implementation of new market designs; and the emergence of new business models. Within the context of the *Innovation landscape for a renewable-powered future* report, IRENA's analysis focuses on one concrete application for digital technologies: the integration of VRE technologies into power systems. Accordingly, three specific digital technology groups are studied further: 1) the internet of things (IoT); 2) artificial intelligence (AI) and big data; and 3) blockchain. The analysis indicates that none of these are silver bullets, but rather reinforce each other as part of a toolbox of digital solutions needed to optimise the operations of an increasingly complex power system based on renewable energy.

Figure 1: Increased power sector complexity requires a combination of digital innovations



1 These commonly include: digital twins; chatbots; the IoT; artificial intelligence and big data; distributed ledger technologies (DLT) such as blockchain; and augmented and virtual reality, among others.

This brief provides an overview of artificial intelligence (AI) and big data, along with their applicability in the energy sector. The focus is on how these technologies could contribute to increasing shares of VRE in the power system.

The brief is structured as follows:

I Description

II Contribution to power sector transformation

III Key factors to enable deployment

IV Current status and examples of ongoing initiatives

V Implementation requirements: Checklist

I. DESCRIPTION

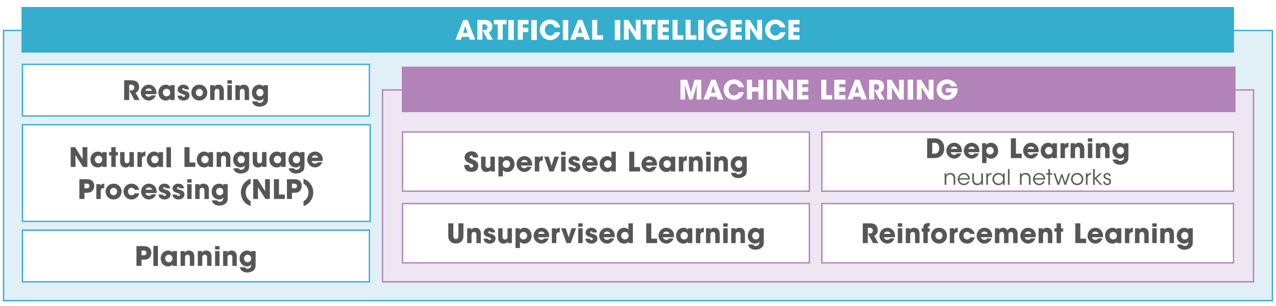
AI and other intelligent tools

From mobile virtual assistants to image recognition and translation to a myriad of other uses, AI is playing an increasingly important role in our modern lives. While the term "AI" was coined in 1956, the past few years have seen rapid advances in AI use in many sectors. Over the coming decades, innovative uses of AI have the potential to increase the insight, efficiency, connectivity, reliability and sustainability of energy systems around the world.

But what is AI? While there is no standard definition, AI is referred to as an area of computer science that focuses on the creation of intelligent machines that work and react more like humans. **AI refers to systems that, in response to data observed, collected and analysed, change behaviour without being explicitly programmed** (WCO, 2019). At its core, AI is a series of systems that act intelligently, using complex algorithms[2] to recognise patterns, draw inferences and support decision-making processes through their own cognitive judgement, the way people do. AI can be "weak", in which case it is focused on narrow tasks (personal assistants like Apple's Siri, chess-playing software, etc.) or it can be "strong", also known as "general AI", where machines are presented with unfamiliar tasks and are able to find a solution without any human intervention (SearchEnterpriseAI, 2019).

AI and machine learning[3] are often used interchangeably but are not the same thing. Some authors describe machine learning as a subset of AI, where machines gather data and learn for themselves. Machine learning leverages algorithms and models to predict outcomes (IBM, 2019). Other "intelligent" tools, such as natural language processing, deep learning and neural networks, can also fall under the AI umbrella. In this brief, all such tools will be called "AI" or "machine learning", as appropriate.

Figure 2: Collection of intelligent tools clustered as AI in the context of this brief



Adapted from IBM (2019).

2 An algorithm is a process or a set of rules to be followed in calculations or other problem-solving operations, especially by a computer. Algorithms can perform calculation, data processing, automated reasoning and other tasks.

3 Machine learning is a form of AI that enables a system to learn from data rather than through explicit programming. However, machine learning is not a simple process. As the algorithms ingest training data, more precise models can be produced. A machine-learning model is the output generated when a machine-learning algorithm has been trained with data. After training, when a model is given an input, it will produce an output. For example, a predictive algorithm will create a predictive model. Then, when the predictive model is provided with data, it will produce a prediction based on the data that trained the model (IBM, 2019).

The use of AI continues at an impressive rate in e-commerce, politics, manufacturing, engineering, health care, transportation, finance, telecommunications, services and energy. And the impact is becoming ever more apparent (DNV GL, 2018). In addition, the costs of applying AI are falling as the ease of use increases. Combined with the explosion of processing power and the generation and availability of large amounts of useful data, AI models are increasingly able to perform specific tasks without explicit instructions.

Here is a simple, practical example of machine learning:

A model is fed vast quantities of data, in this case a series of images (e.g. 100 000 pictures of dogs and 100 000 pictures of cats). All are labelled either "cat" or "dog" so that the computer can categorise their distinguishing features accordingly. The machine-learning model then applies what it has learned to new photos, without labels, and decides whether those are cats or dogs based on what it learned from the training dataset of 200 000 animal photos.

Big data

Extremely large datasets, both structured and unstructured, are referred to simply as "big data". The interlink between AI and big data is the need for intelligent tools to effectively analyse the large amounts of data being generated and convert it into value for the power sector (SAS, 2019).

The abundance of big data, along with the exponential growth in processing power witnessed over the past few decades, has created the ideal setting for AI. Globally in 2018, five exabytes[4] of data were generated each and every day (Cisco, 2018). By 2025, it is estimated that 463 exabytes of data will be created each day (Desjardins, 2019). As the world steadily becomes more connected, with an ever-increasing number of electronic devices, data generation will continue to grow, requiring increasingly intelligent systems able to analyse this trove of data but also enabling the creation of ever more insightful AI, as the models can be better trained.

For the power sector, a major source of this new data will be the vast amount of internet-connected (IoT) devices, set to grow from 25 billion devices today to 75 billion by 2025 (Statista, 2018) (see the Innovation Landscape brief *Internet of things* [IRENA, 2019b]). IoT and new digital devices, such as smart appliances, intelligent inverters and home battery storage systems, are being powered by advances in data, analytics and connectivity. The use of AI is most useful for decision making in complex systems with massive amounts of data, where more traditional data analysis tools may be too time-consuming or may struggle to find optimal solutions (IBM, 2019).

As the power sector becomes increasingly complex, intelligent tools such as AI are needed to effectively manage systems and derive value from all the new data being generated. As AI algorithms ingest this data, it becomes possible to produce more precise models (IBM, 2019).

4 One exabyte is equal to one quintillion (1 000 000 000 000 000 000) bytes.

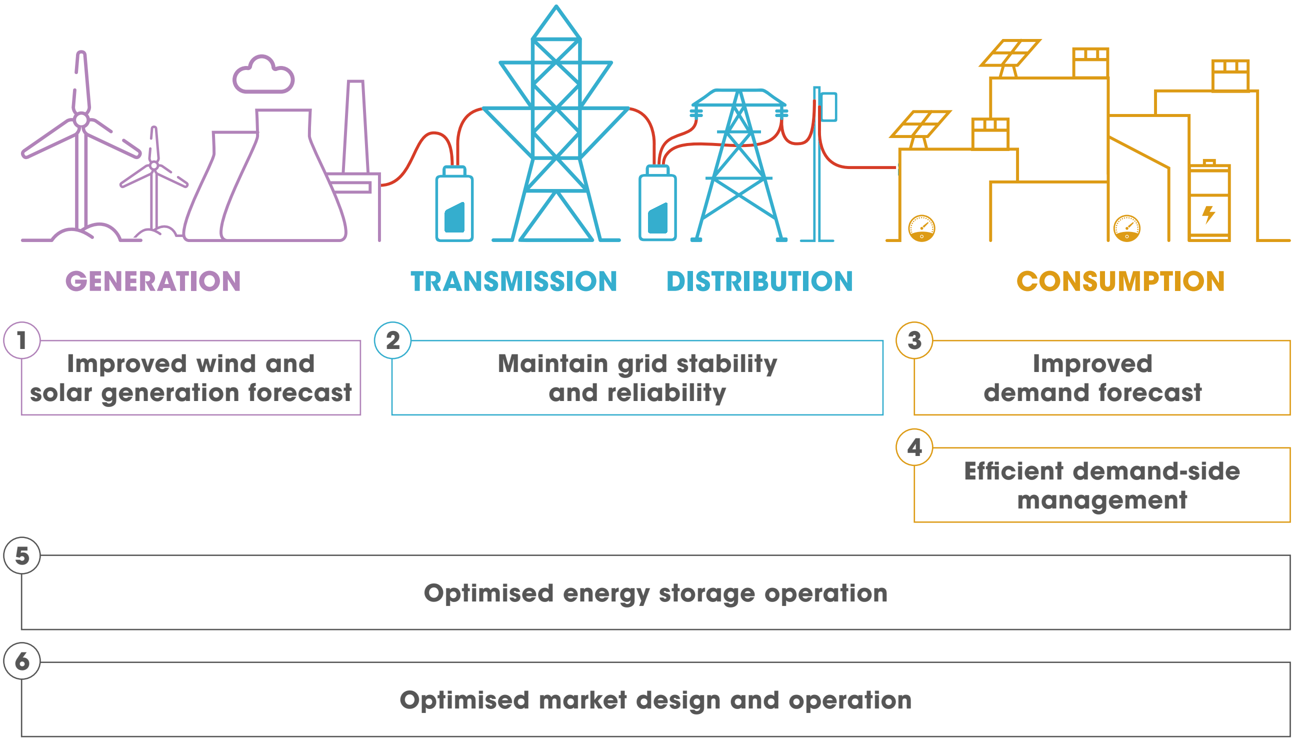
II. CONTRIBUTION TO POWER SECTOR TRANSFORMATION

The power sector is undergoing a major transformation with the increased deployment of renewable energy technologies (solar PV and wind) that provide variable energy supply, distributed energy resources (DERs)[5], bidirectional flow of electricity, large flows of data collected by IoT and other devices, increased use of energy storage, and the evolving role of utilities and consumers. Many system operation decisions are still taken and enacted manually, or with a basic level of automation, because of the small number of automatically controllable resources. However, the developments mentioned above would allow for a larger number of automatically controllable resources responding to needs from several stakeholders (*e.g.* consumers, generators, transmission and distribution operators, retailers). This advanced level of control enables optimisation of the system with more distributed resources while maximising system flexibility and reducing the cost of operating a system with high shares of VRE. Thus, the role of AI and big data is evolving from a facilitating and optimising tool to a necessity for smart and fast decision making.

As previously discussed, AI and other digital technologies can support the renewable energy sector in a variety of ways. Most of the advances currently supported by AI have been in advanced weather and renewable power generation forecasting and in predictive maintenance. In the future, AI and big data will further enhance decision making and planning, condition monitoring, inspections, certifications and supply chain optimisation and will generally increase the efficiency of energy systems. However, this brief focuses on facilitating greater integration of VRE into power systems, where six main categories of application for AI can be identified, as shown in Figure 3.

5 DERs are small or medium-sized resources directly connected to the distribution network. DERs include distributed generation; energy storage (small-scale batteries); and controllable loads, such as electric vehicles, heat pumps or demand response (see the Innovation Landscape brief *Market integration of distributed energy resources* [IRENA, 2019c]).

Figure 3: Emerging applications of AI for VRE integration



Note: The categories listed are not exhaustive but identify concrete areas where AI is, at present, being used or tested for VRE integration.

1. Improved renewable energy generation forecast

Improved weather forecasting is one of the main AI applications that will improve the integration of renewables into the power system. Solar and wind generation provide an enormous amount of data, and renewable technologies have benefited from sensor technology being long established. Big data and AI can produce accurate power generation forecasts that will make it feasible to integrate much more renewable energy into the grid (MIT, 2014). For example, in 2015, IBM was able to show an improvement of 30% in solar forecasting while working with the US Department of Energy's SunShot Initiative. The self-learning weather model and renewable generation forecasting technology integrated large datasets of historical data and real-time measurement from local weather stations, sensor networks, satellites and sky image cameras (IBM, 2015).

Accurate VRE forecasting at shorter time scales can help generators and market players to better forecast their output and to bid in the wholesale and balancing markets, while avoiding penalties. For system operators, accurate short-term forecasting can improve unit commitment, increase dispatch efficiency and reduce reliability issues, and therefore reduce the operating reserves needed in the system.

A successful example is that of EWeLiNE, a research project using machine learning-based software in Germany, finished in 2017, and Gridcast, a follow-up project. Through AI, both projects forecasted power generation using data from solar sensors, wind turbine sensors and weather forecasts, which helped minimise curtailment of excess power generation.

2. Maintain grid stability and reliability

By providing accurate demand and supply forecasts, AI can further optimise the operation of the system, in particular in the context of decentrazlised systems with bidirectional electricity flow, which increases complexity in power systems.

Power distribution grid operators are confronted with great challenges because the number of decentralised energy generation systems, such as solar PV, has grown rapidly. The deployment of renewable energy technology leads to fluctuations and irregular peak loads in the power grid. AI can ensure that the power grid always operates at optimal load and can optimise the energy consumption of customers. Ideally, the electricity generated by the solar PV system in the home or within the neighbourhood grid would be consumed.

For example, in Riedholz, Switzerland, four companies (Adaptricity, AEK, Alpiq and Landis+Gyr), together with the Canton of Solothurn, are testing how AI solutions can ensure future grid stability and minimise investments in costly grid expansion in a pilot project called SoloGrid. The project investigates how GridSense, an algorithm that learns user behaviour through AI, can 1) control the primary electricity consumers, such as heat pumps, boilers, household batteries and charging stations for electric vehicles, and 2) integrate measurement data from solar PV systems for optimal grid operation. The algorithm continuously measures parameters such as grid load, consumption and generation, including weather forecasts and electricity prices, and optimises the generation and consumption of power. The technology reduces peak loads in the power grid, balances the loads and stabilises the distribution grid (Warren, 2019).

Grid congestion at the transmission and distribution level is an important factor that slows the integration of wind and solar PV electricity into power systems. AI can increase the capacity of the power grids and reduce the need for new lines through better use of existing lines as a function of weather conditions. This is the case in, for example, the dynamic line rating projects implemented by the company Ampacimon or being investigated at the Karlsruhe Institute of Technology in the "PrognoNetz" project (KIT, 2019). AI-based systems, using large amounts of weather data, can ensure optimal use of existing power grids by adapting operation to the weather conditions at any time and therefore reducing congestion.

AI can also improve safety, reliability and efficiency in the power system by automatically detecting disturbances. The technology can enable automated data processing in real time and detect cases of emergency or appliance failure. As an example, researchers have provided AI models with examples of typical system outages to allow the algorithm to gradually learn to distinguish – and precisely categorise – normal operating data from defined system malfunctions. The algorithm was able to make split-second decisions on where there was an anomaly or fault, as well as the type and location of that disturbance. If one power plant should fail, an abrupt spike can be expected in the load placed on the other power plants. The increased load slows down the generators, and the frequency decreases. This calls for rapid (less than 500 millisecond [ms]) countermeasures, because if the frequency sinks below a threshold value, the operator may be forced to cut off sections of the grid for the sake of system stability. Since the algorithm can reach a decision within 20–50 ms, there would be sufficient time to implement the appropriate fully automated countermeasures. The algorithm is ready to be implemented, according to researchers, and work continues on the control and regulation of the relevant countermeasures (Fraunhofer, 2019).

3. Improved demand forecast

Accurate demand forecasting, together with renewable generation forecasting, can be used to optimise economic load dispatch as well as to improve demand-side management and efficiency.

Consumers produce an increasing stream of data that comes through the power grid itself. There has been a significant push to install smart meters that are able to send the information to utility providers as often as hourly. From this data, AI can predict not only network load but also consumption habits, and can accurately draw a consumption pattern for each consumer. This becomes even more relevant with the current deployment of DERs, such as electric vehicles, heat pumps and solar PV panels, which change the traditional load shape entirely.

BeeBryte, for example, is a French startup that uses AI to predict a building's thermal energy demand in order to produce heating and cooling at the right times, maintaining comfort and temperature within an operating range set by the customer. This can result in savings of up to 40% on utility bills thanks to a combination of efficiency gains and load shifting to periods when electricity is cheapest, when renewable electricity is available in the system (BeeBryte, 2018).

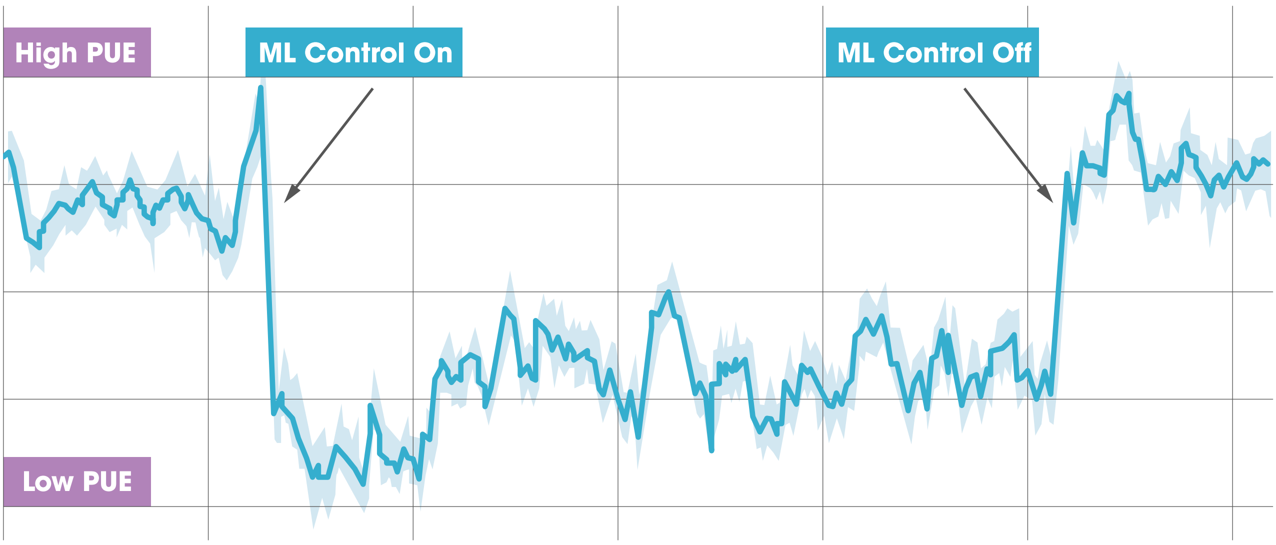
Understanding the consumer's habits, values, motivations and even personality further bolsters the balancing and effectiveness of a smart grid. It also allows policies to be created more effectively and enables an understanding of the human motivations associated with renewable energy adoption and how to possibly change consumer behaviour to optimise the whole energy system (Jucikas, 2017).

4. Efficient demand-side management

Demand-side management is witnessing a myriad of AI and big data activity, with advancements being made in demand response, energy management systems and overall energy efficiency. Using weather forecasts, occupancy, usage, energy prices and patterns identified in consumer behaviour, AI can optimise the energy management of a consumer's house, reducing their electricity bill.

Google's DeepMind AI, for example, reduced the energy used for cooling at one of Google's data centres by 40% in 2016 (a 15% overall reduction in power usage) using only historical data collected from sensors within the data centre (*e.g.* temperatures, power, pump speeds, setpoints) to improve data centre energy efficiency. The AI system predicts the future temperature and pressure of the data centre over the next hour and gives recommendations to turn the consumption on or off. The graph below shows a typical day of testing, including when Google turned the machine-learning recommendations on and off (Evans and Gao, 2016).

Figure 4: Machine-learning recommendations (on and off) on a typical day



Source: Evans and Gao (2016).
ML = machine learning; PUE = power usage effectiveness. The data centre industry uses the measurement PUE to measure efficiency. A PUE of 2.0 means that for every watt of computing power, an additional watt is consumed to cool and distribute power to the IT equipment. A PUE closer to 1.0 means nearly all the energy is used for computing.

In 2018, DeepMind took these innovations to the next level. Instead of its recommendations being implemented by people, DeepMind's AI system now directly controls data centre cooling, while remaining under the expert supervision of data centre operators. This cloud-based control system now delivers energy savings in multiple Google data centres (Gamble and Gao, 2018).

IBM has shown similar results using their machine-learning techniques (IBM, 2018a). Additionally, Grid Edge, an UK based company, reduced energy consumption in shopping centres and airports and provided energy managers the ability to better manage energy usage through the prediction of weather and of customer or new aircraft movements.

5. Optimised energy storage operation

Energy storage systems, in the form of large-scale batteries, aggregated small batteries ("behind the meter") or plugged-in electric vehicles, are emerging as key enablers for renewable energy integration. AI can help operate these technologies in a more efficient way, maximising renewable electricity integration (including the reduction of generation forecast errors), minimising prices for electricity consumed locally and maximising returns for the owners of the storage system. For large-scale energy storage systems, this includes decisions on storing excess renewable electricity in a network of batteries and discharging the batteries to meet demand at a later point in time, while considering forecasted demand, renewable energy generation, prices and network congestion, among other variables.

As storage batteries can be activated quickly and can be used to manage excessive peaks and minimise the back-up energy needed from diesel generators, coal-fired power plants or other peaker plants, AI can be used to predict and make energy storage management decisions.

The speed and complexity of managing energy storage systems in a dynamic environment, encompassing many variables, requires advanced AI. AI research is studying decision making on a scale and with a complexity that surpasses that of a human operator, especially for networks of thousands of mixed energy storage units (electrical, thermal, etc.) installed at the end consumer side, at households or industrial installations.

In addition, AI can help estimate and extend the useful life of a storage unit by applying predictive logic algorithms to the charging and discharging data. Owners will deploy their storage pack according to the compensation for the services provided by the battery, as well as the impacts these services have on the state of health of the batteries. California-based company Stem has developed Athena, which uses AI to map out energy usage and allow customers to track fluctuations in energy rate to more efficiently use storage.

In Australia, for example, Tesla's Hornsdale battery was a wake-up call, according to United States-based software-as-a-service platform provider AMS. By using AI, versatile battery storage systems can optimise opportunities to purchase electricity from the grid when prices are low and then to sell back to the market when prices are high. The Hornsdale battery has operated via an autobidder developed by Tesla, which has allowed the project to capture the best revenue streams to a degree that could not have been achieved by human bidders alone. "Relative to a human trader, algorithmic bidding software can increase the revenues of a battery by about five-times", according to AMS. In its first year of operation, the Hornsdale battery generated an estimated $24 million in revenue, while also providing between a $40 and $50 million reduction in frequency control ancillary service costs, savings that are ultimately to the benefit of consumers (Mazengarb, 2019). Cost savings such as these are likely to lead to an influx of algorithm development aimed at operating batteries in the most lucrative way.

6. Optimised market design and operation

Sophisticated models based on AI are also being deployed to optimise close to real-time market operations. Such optimisation relies on the analysis of large streams of diverse data to enable rapid response to market changes.

Intraday trading is particularly useful for adjusting to unforeseen changes in power production and consumption by putting market mechanisms to use before control reserves become necessary. This allows a power plant operator who suddenly loses production in a single block to buy additional power from other participants on the market and maintain the balancing group. Intraday trading is therefore a key component for direct marketing of power produced by renewable energy when quickly changing weather results in an unplanned shortfall or surplus of power from solar or wind power plants. The speed and complexity of operating intraday markets in a dynamic environment that encompasses many variables can be beyond a human operator; this would be an ideal application for advanced AI.

When coupling different markets to create regional markets, the complexity in market operations increases even more. An AI-based algorithm called EUPHEMIA was developed to calculate day-ahead electricity prices across Europe and allocate cross-border transmission capacity on a day-ahead basis. EUPHEMIA is used daily to compute in a coupled way day-ahead electricity prices for 25 European countries (Austria, Belgium, Croatia, Czech Republic, Denmark, Estonia, Finland, France, Germany, Hungary, Ireland, Italy, Latvia, Lithuania, Luxembourg, the Netherlands, Norway, Poland, Portugal, Romania, Slovakia, Slovenia, Spain, Sweden and the United Kingdom), with an average daily value of matched trades over EUR 200 million (NEMO Committee, 2019).

In terms of market design, AI can increase time granularity in electricity markets and enable real-time markets. The use of AI is being explored to support trading and dispatch decisions for generation assets in the close to real-time trading markets, focusing on when the generators should commit to trade to maximise the option value of flexible capacity. An example is Origami Energy, a startup company based in Cambridge, United Kingdom, using AI to predict asset availability and balancing mechanism market prices in near real time to successfully bid in the frequency response markets.

With the use of advanced analytics and machine learning, various operational optimisation problems can be solved and new insights for medium- and long-term strategy can be derived – such as to forecast when an asset will be available, the value of flexibility and how an asset should best be used to derive most value (Pöyry, 2018).

Other AI applications in the power sector

In addition to directly supporting the integration of VRE, AI can be used in other applications for power systems. These include increased visibility into energy leakage, consumption patterns and equipment functioning status. For instance, predictive analytics can take sensor data from a wind turbine to monitor wear and tear and predict with a high degree of accuracy when the turbine would need maintenance. Strategy in targeting where to deploy the real-time sensing is also necessary. For example, some assets last a very long time and outlast the sensors several times over.

With the help of AI, GE in Japan succeeded in enhancing wind turbine efficiency, reducing maintenance costs by 20% and increasing power output by 5% (Nikkei, 2017). McKinsey's Utilityx achieved maintenance and replacement cost savings of 10–25% through predictive maintenance (McKinsey & Company, 2019). Uruguay's National Agency for Research and Innovation and the Uruguay Ministry of Industry, Energy and Mining are also exploring AI for the predictive maintenance of wind power plants in a project conducted jointly with the utility UTE and the School of Engineering of the University of the Republic[6].

Where such markets are in place, AI could also enhance the integrity of the electricity market as well as transparency in the regulator's tasks of monitoring and investigating the trading activity. For example, the European Agency for the Cooperation of Energy Regulators (ACER) uses a market surveillance system called ARIS, which automatically screens and analyses the data collected to identify anomalies that might constitute cases of market abuse according to European legislation (ACER, 2015).

6 Based on discussions during the IRENA Innovation Day in Uruguay, July 2019.

III. KEY FACTORS TO ENABLE DEPLOYMENT

Technological maturity

AI is not a new technology. However, the recent advances in processing power, data collection and communications are opening the door to AI applications in the power sector. Nevertheless, more investment and research are required to maximise its potential. This investment includes funding for research and development.

For example, through algorithm tuning (*i.e.* optimisation of the choice of parameters whose value is set before the machine-learning process starts), predictive models can become more precise.

Availability and quality of data

One of the key challenges with AI is the quality of the large datasets (big data) with which to develop the models. The data available today is not always sufficient or of good enough quality to develop systems that can handle complex scenarios. However, digital technologies are evolving to address these issues, (*e.g.* cloud servers and better management of data), which leads to less data being needed and better structuring of data, which in turn has an impact on the need to perform more calculations.

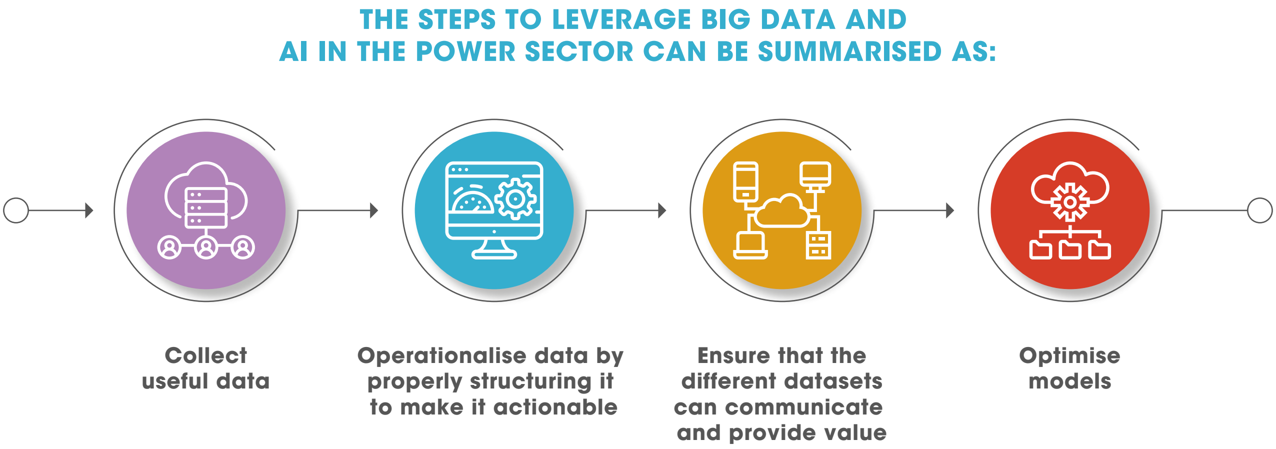
Fortunately, the expansion of computing power seen in recent years is now being complemented by exponential growth in the availability of data, due largely to IoT devices coming online (see the Innovation Landscape brief *Internet of things* [IRENA, 2019b]).

Another concern regarding data is the problem of bias. If the source of the data being fed into the AI systems is biased in nature, then the decision-making processes will also be biased, leading to erroneous or undesired results. Thus, bias in AI systems must be reduced as far as possible. Also, since the machines are developed with their own sense of discretion, at times it may be difficult or impossible to predict the decision made by the machines or explain the logic used.

Opening up public sector data can spur private sector innovation. Setting common data standards can also help (Chui et al., 2018). For example, in the European Union, "Regulation (EU) No. 543/2013 of 14 June 2013 on submission and publication of data in electricity markets" established the rules for the Transparency Platform, which is an online data platform for European electricity system data (European Union, 2013). The Transparency Platform is operated by the European Network of Transmission System Operators for Electricity and contains, among other information, data items on load, generation, transmission, balancing and outages, which could be used by private sector companies to develop new business models and offer new services to consumers.

The availability of end consumer data, like data on loads from household consumers and their electric vehicle charging patterns, could be a concern from a privacy point of view. For example, in the European Union, "Regulation (EU) 2016/679 of 27 April 2016 on the protection of natural persons with regard to the processing of personal data and on the free movement of such data" sets strict rules (European Union, 2016).

Figure 5: The steps to leverage big data and AI in the power sector



Growing importance of cybersecurity

Like any information and communications technology (ICT) advancement, an important factor for consideration is cybersecurity. Cybersecurity will be a growing issue as both ICT and electricity networks become increasingly interconnected and new digital technologies and means of communication become widespread. Attacks on grids have increased in recent years, and some have proven successful. These attacks pose a threat to the critical infrastructure that keeps the energy system going – not just the electricity grid, but the highly interconnected and interdependent natural gas, water, communications and fuel distribution systems (AEE Institute, 2018).

The introduction of advanced and intelligent technologies into the power sector presents both opportunities and challenges. The increasing number of connected devices has provided a vast surface area for attacks that exploit IoT devices with weak security, as shown recently with the Mirai IoT botnet and others (Cloudflare, 2019). Modern power grids will open new modes of communication and interaction between increasingly diverse and numerous market participants (*e.g.* consumers via aggregators) and connected devices. For this reason, as well as having opportunities to reap new benefits, modern power grids are exposed to security vulnerabilities in new ways (Walton, 2018).

But AI may help address the issue of cybersecurity. IBM, for example, is working to reduce this risk, training AI to improve its knowledge so as to "understand" threats and cyber risk; identify relationships between threats, such as malicious files, suspicious IP addresses or insiders; and reduce the amount of time security analysts need to make critical decisions and launch an orchestrated response to remediate the threat (IBM, 2018b). Protections under development aim to make an increasingly complex, interactive and distributed electricity system more resilient against cyberattacks (AEE Institute, 2018).

Microsoft has also introduced the Azure Sphere, a secured microcontroller unit running its own operating system and supported by Microsoft cloud services for periodic updates, in an effort to deliver end-to-end IoT security that responds to emerging threats (Microsoft, 2019). For more information on how these devices can be used to automate and secure demand-side management, see the Innovation Landscape brief *Internet of things* (IRENA, 2019b).

Policy makers will need to strike a balance between supporting the development of AI technologies and managing any risks from malicious actors, as well as the irresponsible use of AI techniques and the data they employ. Policy makers have an interest in supporting broad adoption of AI, since AI can lead to greater labour productivity, economic growth and societal prosperity. Tools to help policy makers include public investments in research and development as well as support for a variety of training programmes, which can help nurture AI talent.

Training and re-skilling of energy sector professionals

For actors in the energy sector to exploit the full potential of digital transformation, automating tasks to provide the time and resources for greater innovation is not enough. The radical shift that digitalisation may usher in also brings with it the need to change the way human capital is managed and developed. Energy sector actors, and enterprises in general, need to invest in re-skilling and training their employees to manage and operate power assets and systems that are digitalised, otherwise the promise of a more effective and efficient energy sector will not be fully realised. Re-skilling is key to avoiding loss of jobs. Making the right decisions about what to automate, prioritisation for automation, extent of automation and where to apply AI, as well as decisions about people whose roles are impacted, still rest within the human domain. Learning can impact these decisions positively.

IV. CURRENT STATUS AND EXAMPLES OF ONGOING INITIATIVES

The following is a non-exhaustive sampling of companies, consortiums and foundations working at the intersection of AI and the power sector, particularly related to VRE integration.

Table 1 Companies, consortiums and foundations working on IoT in the power sector

Project (company)	Service provided	Description
BeeBryte (France, Singapore)	**Demand forecast and demand-side management**	BeeBryte aims to minimise utility bills with AI algorithms and automated control of heating-cooling equipment (*e.g.* HVAC), pumps, electric vehicle charging points or batteries. Using advanced weather forecasts, occupancy, consumption and electricity price signals, BeeBryte maintains processes and temperature within an operating range set by the customer, resulting in up to 40% savings.
DCbrain (France)	**Grid stability and reliability**	DCbrain enables the optimisation of flows and consumptions, the identification and prevention of network anomalies and the simulation of network evolution.
DeepMind, Google (United States)	**Demand forecast and demand-side management**	DeepMind develops programs that can learn to solve complex problems without needing to be taught how. DeepMind has tested its machine-learning algorithms at Google's data centres in an effort to reduce power consumption.
DeJoule, Smart Joules (India)	**Demand forecast and demand-side management**	DeJoule is an air conditioning optimisation platform with a built-in software that uses AI to facilitate demand-side management and enhance the efficiency and performance of air conditioning systems while decreasing costs for consumers.
EUPHEMIA, N-SIDE (Europe)	**Optimised market operation**	EUPHEMIA is a coupling algorithm that integrates European day-ahead energy markets to determine spot prices and volumes. It covers 25 European countries (Austria, Belgium, Croatia, Czech Republic, Denmark, Estonia, Finland, France, Germany, Hungary, Ireland, Italy, Latvia, Lithuania, Luxembourg, the Netherlands, Norway, Poland, Portugal, Romania, Slovakia, Slovenia, Spain, Sweden and the United Kingdom).
EWeLiNE (Germany)	**Renewable energy generation forecasting**	EWeLiNE uses AI to predict the supply of renewable energy days in advance. EWeLiNE takes real-time data from solar power plants and wind turbines around Germany and feeds it into an algorithm that calculates the renewable energy output for the next 48 hours. This algorithm uses machine learning, and the researchers compare real data with EWeLiNE predictions to refine the algorithm and improve its accuracy.
Fraunhofer (Germany)	**Grid stability and reliability**	Fraunhofer Institute has developed an AI algorithm that can log and compress up to 4.3 million datasets a day, process that data to develop accurate predictions for grid operators, detect any network anomalies and act on them within 20–50 milliseconds .

Project (company)	Service provided	Description
Grid Edge (United Kingdom)	**Grid stability and reliability**	IBM is using analytics to power decision making; sustainably balance supply and demand to deliver safe, secure and reliable electricity service from conventional and renewable energy sources; monitor and manage grids holistically; improve network reliability; resolve issues faster; and lower costs through smart metering.
IBM Watson (United States)	**Grid stability and reliability**	IBM is using analytics to power decision making; sustainably balance supply and demand to deliver safe, secure and reliable electricity service from conventional and renewable energy sources; monitor and manage grids holistically; improve network reliability; resolve issues faster; and lower costs through smart metering.
Infosys (Global, India)	**Demand forecast and demand-side management**	Infosys supports energy sector participants by applying machine learning to the data generated by advanced sensors, smart meters and intelligent devices behind the meters. By applying AI to this data, the industry can gather granular consumption insights that it can use to propose new services to consumers, while creating an opportunity for retail suppliers.
MindSphere, Siemens (Germany)	**Demand forecast and demand-side management**	MindSphere is a cloud-based solution that collects and analyses IoT data to provide demand-side management and higher control of industrial-scale connected devices.
Nnergix (Spain, United States)	**Renewable energy generation forecast**	Nnergix provides solar and wind power forecasting for energy markets and system operators.
PSR and Kunumi (Brazil)	**Advanced forecasting System and market operation**	PSR and Kunumi are integrating AI and new analytical methods to provide forecasting and optimise energy systems under uncertainty, including operations, planning and trading.
SmartNet (European Union)	**Grid stability and reliability**	SmartNet provides instruments to improve co-ordination between transmission system operators and distribution system operators by exchanging monitoring information as well as information for the acquisition of ancillary services from actors in the distribution segment.
Tomorrow (Denmark)	**Demand forecasting and demand-side management**	Tomorrow created an AI algorithm that automatically extracts insights about CO_2 emissions from various types of data. These insights are then used by different tools, such as the ElectricityMap, which displays in real time the CO_2 emissions of electricity generation, imports and exports in different countries worldwide. The algorithm could facilitate demand-side management by using connected devices only when the CO_2 content of electricity is low (*e.g.* charging electric vehicles with renewable electricity).
Utilityx, McKinsey (United States)	**Predictive maintenance**	Utilityx helps asset managers optimise productivity using predictive maintenance. Advanced analytics are used to transform network data into a condition-based strategy, driven by the health and criticality of an asset.
Verv (United Kingdom)	**Demand forecast and demand-side management**	Verv home energy assistant seeks to reduce consumer energy bills by using AI to learn about home appliances and their behaviour, giving customers real-time energy usage statistics.

Table data sourced from individual websites. TWh = terawatt-hours.

V. IMPLEMENTATION REQUIREMENTS: CHECKLIST

TECHNICAL REQUIREMENTS	**Hardware:** • Smart grids and smart meters to collect large amounts of high-quality, granular data **Software:** • Software specific to the AI technology used in a particular system • Cloud platform (if data is not stored locally) • Large amounts of granular data to train models **Human expertise:** • Data scientists able to develop machine-learning algorithms and continuously improve models that can be applied to the power sector, especially to VRE integration • Renewable power sector stakeholders able to understand digital technologies and work with data scientists to apply AI techniques to integrate VRE into power systems (*e.g.* system operators working with ICT experts or data scientists gaining expertise in the power sector)
POLICIES NEEDED	• Assess the impact of AI on jobs, promote re-skilling to prevent job loss, and create new job opportunities • Allow public access to data so that anyone can use or develop digital technologies • Inform and empower consumers, including prosumers, to participate in demand-side management programmes • Enable funding of research and development of AI applications
REGULATORY REQUIREMENTS	• Define data privacy regulation for consumers, and create incentives to participate in pilot projects as data providers • Define cybersecurity protocols • Define protocols for the interoperability of big data • Ensure algorithms comply with existing power sector regulation, or adapt, where necessary
STAKEHOLDER ROLES AND RESPONSIBILITIES	• **System operators:** Adopt an innovative approach to system operation by enhancing co-operation among distribution and transmission system operators; account for evolving role of distribution system operators • **DER owners/operators** (*e.g.* aggregators)**:** Participate in pilot projects as data providers • **ICT companies:** Work closely with power sector actors (*e.g.* system operators) to develop tailored AI solutions for the integration of VRE into the power system

ACRONYMS AND ABBREVIATIONS

AI	artificial intelligence
DER	distributed energy resource
ICT	information and communications technology
IoT	internet of things
ms	millisecond
PV	photovoltaic
VRE	variable renewable energy

BIBLIOGRAPHY

ACER (2015), *ACER's annual report on its activities under REMIT in 2014*, Agency for the Cooperation of Energy Regulators, Ljubljana, www.acer.europa.eu/Official_documents/Acts_of_the_Agency/Publication/REMIT%20Annual%20Report%202015.pdf.

AEE Institute (2018), *Cybersecurity in a Distributed Energy Future: Addressing the Challenges and Protecting the Grid from a Cyberattack*, Advanced Energy Economy Institute, Washington, DC, https://info.aee.net/hubfs/Cybersecurity_FINAL_WP_AEEInstitute_1.18.18.pdf.

BeeBryte (2018), "Unlocking the '5th fuel': Increased energy efficiency with machine learning + big data", BeeBryte, https://innovationweek.irena.org/-/media/Files/IRENA/Innovation-Week/SessionalDocuments/IRENA-IW18-AI-02-Dirand-Unlocking-the-fifth-fuel-05-Sept-18.pdf.

Cisco (2018), "Internet of things (IoT) data continues to explode exponentially. Who is using that data and how?", Cisco, https://blogs.cisco.com/datacenter/internet-of-things-iot-data-continues-to-explode-exponentially-who-is-using-that-data-and-how.

Chui, M. et al. (2018), *Notes from the AI Frontier: Applications and Value of Deep Learning*, McKinsey Global Institute, New York, www.mckinsey.com/~/media/mckinsey/featured%20insights/artificial%20intelligence/notes%20from%20the%20ai%20frontier%20applications%20and%20value%20of%20deep%20learning/notes-from-the-ai-frontier-insights-from-hundreds-of-use-cases-discussion-paper.ashx.

Cloudflare (2019), "What is the Mirai botnet?", Cloudflare, www.cloudflare.com/learning/ddos/glossary/mirai-botnet.

European Union (2013), "Regulation (EU) No. 543/2013 of 14 June 2013 on submission and publication of data in electricity markets and amending Annex I to Regulation (EC) No 714/2009 of the European Parliament and of the Council", *Official Journal of the European Union*, L 163/1, https://eur-lex.europa.eu/LexUriServ/LexUriServ.do?uri=OJ:L:2013:163:0001:0012:EN:PDF.

European Union (2016), "Regulation (EU) 2016/679 of the European Parliament and of the Council of 27 April 2016 on the protection of natural persons with regard to the processing of personal data and on the free movement of such data, and repealing Directive 95/46/EC (General Data Protection Regulation)", *Official Journal of the European Union*, L 119/1, https://eur-lex.europa.eu/legal-content/EN/TXT/PDF/?uri=CELEX:32016R0679.

Desjardins, J. (2019), "How much data is generated in a day?", World Economic Forum, www.weforum.org/agenda/2019/04/how-much-data-is-generated-each-day-cf4bddf29f.

DNV GL (2018), "Making renewables smarter. The benefits, risks and future of artificial intelligence in solar and wind energy", DNV GL, www.dnvgl.com/publications/making-renewables-smarter-104362.

Evans, R., and J. Gao (2016), "DeepMind AI reduces Google data centre cooling bill by 40%", Google DeepMind, https://deepmind.com/blog/deepmind-ai-reduces-google-data-centre-cooling-bill-40.

Fraunhofer (2019), "Artificial intelligence automatically detects disturbances in power supply grids", Fraunhofer, www.fraunhofer.de/en/press/research-news/2019/research-news-april-2019/artificial-intelligence-automatically-detects-disturbances-in-power-supply-grids.html.

Gamble, C. and J. Gao (2018), "Safety-first AI for autonomous data centre cooling and industrial control", Google DeepMind, https://deepmind.com/blog/safety-first-ai-autonomous-data-centre-cooling-and-industrial-control.

GE Power (2018), "GE's digital energy software solutions. End-to-end, integrated and interoperable", GE Power, www.ge.com/power/software.

IBM (2015), "Machine learning helps IBM boost accuracy of U.S. Department of Energy solar forecasts by up to 30 percent", IBM, www-03.ibm.com/press/us/en/pressrelease/47342.wss.

IBM (2018a), "IoT and machine learning to reduce energy use in cooling systems", IBM, www.ibm.com/blogs/research/2018/07/reduce-energy-cooling.

IBM (2018b), "Artificial intelligence for a smarter kind of cybersecurity", IBM, www.ibm.com/security/artificial-intelligence.

IBM (2019), "Data science and machine learning", IBM, www.ibm.com/analytics/machine-learning.

IEA (2017), *Digitalization & Energy,* International Energy Agency, Paris, www.iea.org/publications/freepublications/publication/DigitalizationandEnergy3.pdf.

IRENA (2019a), *Innovation landscape for a renewable-powered future,* International Renewable Energy Agency, Abu Dhabi, www.irena.org/publications/2019/Feb/Innovation-landscape-for-a-renewable-powered-future.

IRENA (2019b), the Innovation Landscape brief *Internet of things,* International Renewable Energy Agency, Abu Dhabi.

IRENA (2019c), the Innovation Landscape brief *Market integration of distributed energy resources,* International Renewable Energy Agency, Abu Dhabi, https://cms.irena.org/-/media/Files/IRENA/Agency/Publication/2019/Feb/IRENA_Market_integration_2019.ashx?la=en&hash=0159D68FE18E008822F2E8880F8CD2340DE7E540.

Jucikas, T. (2017), "Artificial intelligence and the future of energy", Medium, https://medium.com/wepower/artificial-intelligence-and-the-future-of-energy-105ac6053de4.

KIT (2019), "Artificial intelligence improves power transmission", Karlsruhe Institute of Technology, www.kit.edu/kit/english/pi_2019_055_artificial-intelligence-improves-power-transmission.php.

Mazengarb, M. (2019), "Tesla big battery paves way for artificial intelligence to dominate energy trades", Renew Economy, https://reneweconomy.com.au/tesla-big-battery-paves-way-for-artificial-intelligence-to-dominate-energy-trades-31949.

McKinsey & Company (2019), "Performance management and optimization for the electric-power industry", McKinsey & Company, www.mckinsey.com/solutions/utilityx.

Microsoft (2019), "Azure Sphere", Microsoft Azure, https://azure.microsoft.com/en-us/services/azure-sphere.

MIT (2014), "Smart wind and solar power", MIT Technology Review, www.technologyreview.com/s/526541/smart-wind-and-solar-power.

NEMO Committee (2019), *EUPHEMIA Public Description: Single Price Coupling Algorithm,* NEMO Committee, www.nordpoolspot.com/globalassets/download-center/pcr/euphemia-public-description.pdf.

Nikkei (2017), "AI to propel wind farm efficiency in Japan", Nikkei Asian Review, https://asia.nikkei.com/Business/AI-to-propel-wind-farm-efficiency-in-Japan.

Pöyry (2018), "Pöyry and Infosys jointly introduce an artificial intelligence framework for industry, utilities and infrastructure organisations", Pöyry, www.poyry.com/news/poyry-and-infosys-jointly-introduce-an-artificial-intelligence-framework-for-industry-utilities-and-infrastructure-organisations.

SAS (2019), "Big data: What it is and why it matters", SAS, www.sas.com/en_us/insights/big-data/what-is-big-data.html.

SearchEnterpriseAI (2019), "Predictive storage analytics, AI deliver smarter storage", Tech Target, https://searchstorage.techtarget.com/essentialguide/Predictive-storage-analytics-takes-management-to-the-next-level.

Statista (2018), "Internet of things (IoT) connected devices installed base worldwide from 2015 to 2025 (in billions)", Statista, www.statista.com/statistics/471264/iot-number-of-connected-devices-worldwide.

Walton, R. (2018), "Cybersecurity and the distributed grid: A double-edged sword", Utility Dive, www.utilitydive.com/news/cybersecurity-and-the-distributed-grid-a-double-edged-sword/523285.

WCO (2019), *Study Report on Disruptive Technologies*, World Customs Organization, Brussels.

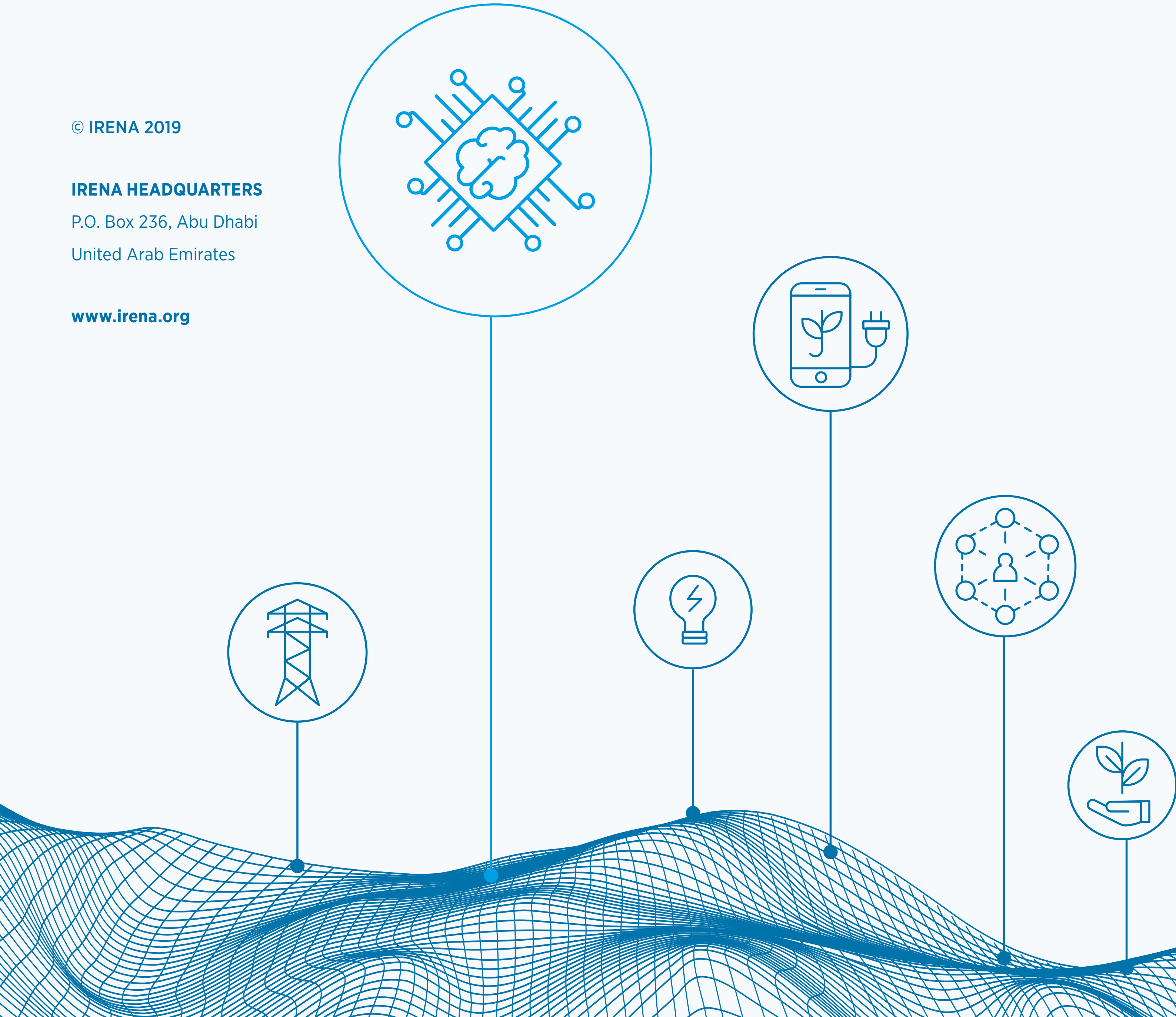
Warren, C. (2019), "Can artificial intelligence transform the power system?", EPRI Journal, http://eprijournal.com/can-artificial-intelligence-transform-the-power-system.

IRENA
International Renewable Energy Agency

ARTIFICIAL INTELLIGENCE AND BIG DATA
INNOVATION LANDSCAPE BRIEF

IRENA HEADQUARTERS
P.O. Box 236, Abu Dhabi
United Arab Emirates

www.irena.org



IRENA
International Renewable Energy Agency

BLOCKCHAIN
INNOVATION LANDSCAPE BRIEF

ISBN 978-92-9260-117-1

Citation: IRENA (2019), *Innovation landscape brief: Blockchain,* International Renewable Energy Agency, Abu Dhabi.

ACKNOWLEDGEMENTS

This report was prepared by the Innovation team at IRENA's Innovation and Technology Centre (IITC) with text authored by Sean Ratka, Francisco Boshell and Arina Anisie, with additional contributions and support by Javier Sesma.

This report benefited from the input and review of experts: Kirsten Hasberg (Aalborg University Copenhagen), Paul Massara (Electron), Douglas Miller (Energy Web Foundation), Mark van Stiphout (European Commission), Philipp Sandner (Frankfurt School Blockchain Center), Pierre Telep (Green Climate Fund), Colleen Metelitsa (GTM Research), Jan Vorrink (TenneT), Morwesi Ramonyai (The Sun Exchange), Marc Johnson (UNFCCC).

Report available online: www.irena.org/publications
For questions or to provide feedback: publications@irena.org

DISCLAIMER

IRENA
International Renewable Energy Agency

1 HOW IT WORKS

Blockchain enables the implementation of **Smart Contracts**, self-executing programms which can be used to better manage systems and integrate higher shares of renewables through automation.

$ ON

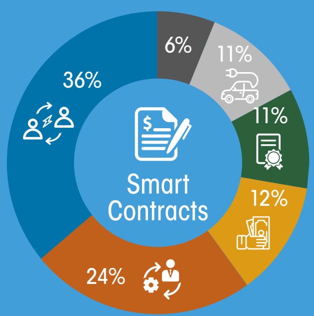
Smart contracts are set to self-execute when specific conditions are met, *e.g.* when peers trade electricity for payment.

2 BENEFITS

- Reduced transaction costs
- Increased transparency
- Increased security
- Increased automation via smart contracts
- Increased participation by new/more actors via decentralisation

3 KEY APPLICATIONS TO INTEGRATE RENEWABLES

- Peer-to-peer power trade
- Grid management and system operation
- Financing renewable energy development
- Management of renewable energy certificates
- Electric mobility



4 SNAPSHOT

- **189** companies working in blockchain in energy
- **71** projects focused on blockchain in energy
- USD **466** million invested in blockchain in power
- About **50%** of projects built on the Ethereum blockchain

*as of September 2018

WHAT IS BLOCKCHAIN?

Blockchain platforms are the base layer on which decentralised applications can be built. Through decentralisation, they can be used to securely record all transactions taking place on a given network without a central intermediary.

BLOCKCHAIN

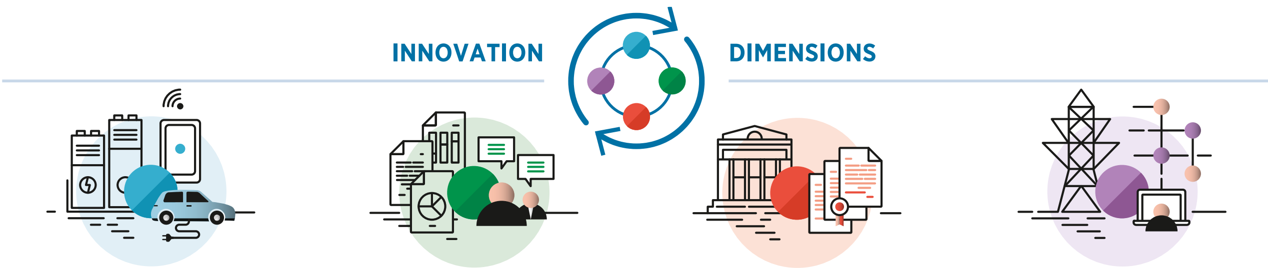
Increased power sector complexity requires greater intelligence. Blockchain can help by managing data more openly and securely while automating transactions via smart contracts.

ABOUT THIS BRIEF

This brief is part of the IRENA project "Innovation landscape for a renewable-powered future", which maps the relevant innovations, identifies the synergies and formulates solutions for integrating high shares of variable renewable energy (VRE) into power systems.

The synthesis report, *Innovation landscape for a renewable-powered future: Solutions to integrate variable renewables* (IRENA, 2019), illustrates the need for synergies among different innovations to create actual solutions. Solutions to drive the uptake of solar and wind power span four broad dimensions of innovation: enabling technologies, business models, market design and system operation.

Along with the synthesis report, the project includes a series of briefs, each covering one of 30 key innovations identified across those four dimensions. The 30 innovations are listed in the figure below.



ENABLING TECHNOLOGIES

1 Utility scale batteries
2 Behind-the-meter batteries

3 Electric-vehicle smart charging
4 Renewable power-to-heat
5 Renewable power-to-hydrogen

6 Internet of Things
7 Artificial intelligence and big data
8 Blockchain

9 Renewable mini-grids
10 Supergrids

11 Flexibility in conventional power plants

BUSINESS MODELS

12 Aggregators
13 Peer-to-peer electricity trading
14 Energy-as-a-service

15 Community-ownership models
16 Pay-as-you-go models

MARKET DESIGN

17 Increasing time granularity in electricity markets
18 Increasing space granularity in electricity markets
19 Innovative ancillary services
20 Re-designing capacity markets
21 Regional markets

22 Time-of-use tariffs
23 Market integration of distributed energy resources
24 Net billing schemes

SYSTEM OPERATION

25 Future role of distribution system operators
26 Co-operation between transmission and distribution system operators

27 Advanced forecasting of variable renewable power generation
28 Innovative operation of pumped hydropower storage

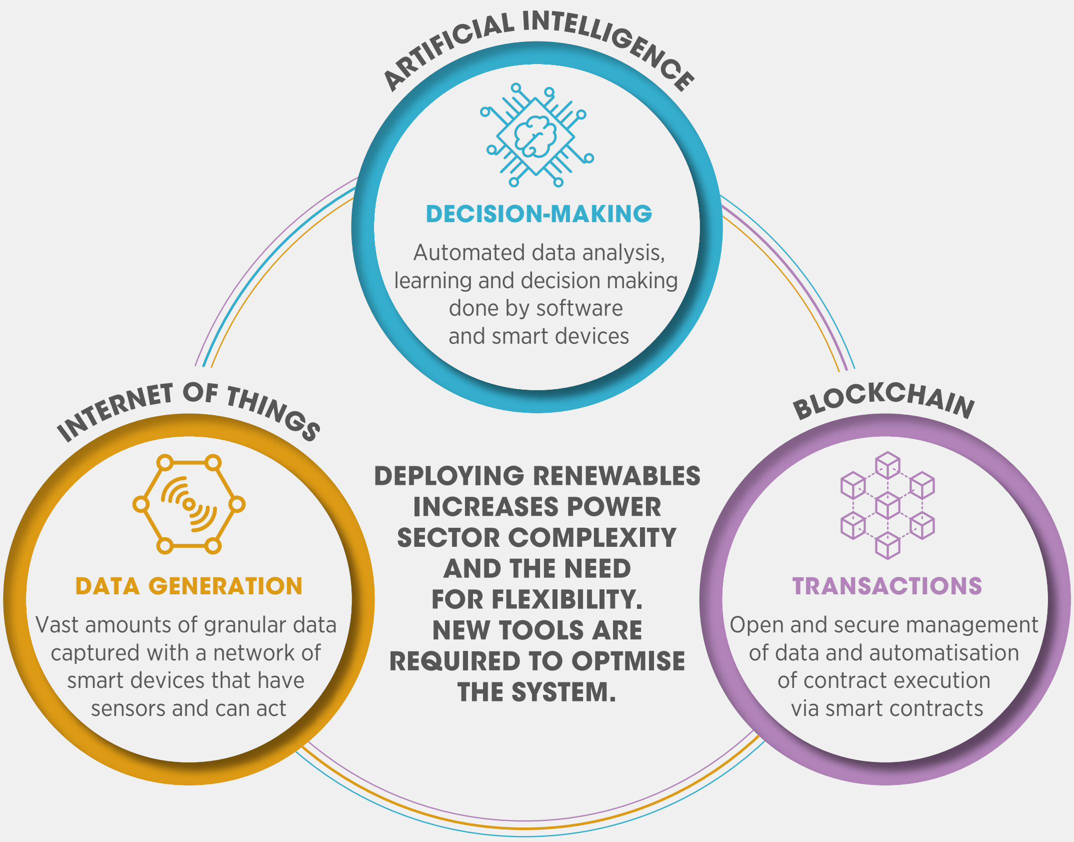
29 Virtual power lines
30 Dynamic line rating

Digitalisation to support VRE integration

Digitalisation is a key amplifier of the power sector transformation, enabling the management of large amounts of data and optimising increasingly complex systems. For the power sector, digitalisation is essentially converting data into value (IRENA, 2019a). The growing importance of digitalisation in the power sector is also a consequence of advances in two other innovation trends: decentralisation and electrification. Decentralisation is led by the increased deployment of small power generators, mainly rooftop solar photovoltaic (PV), connected to the distribution grid. Electrification of transport and buildings (heating and cooling) involves large quantities of new loads, such as electric vehicles, heat pumps and electric boilers. All these new assets on the supply and demand sides are adding complexity to the power sector, making monitoring, management and control crucial for the success of the energy transformation.

Digital technologies[1] can support the renewable energy sector in several ways, including better monitoring, operation and maintenance of renewable energy assets; more refined system operations and control closer to real time; implementation of new market designs; and the emergence of new business models. Within the context of the *Innovation landscape for a renewable-powered future* report, IRENA's analysis focuses on one concrete application for digital technologies: the integration of VRE technologies into power systems. Accordingly, three specific digital technology groups are studied further: 1) the internet of things (IoT); 2) artificial intelligence (AI) and big data; and 3) blockchain. The analysis indicates that none of these are silver bullets, but rather reinforce each other as part of a toolbox of digital solutions needed to optimise the operations of an increasingly complex power system based on renewable energy.

Figure 1: Increased power sector complexity requires a combination of digital innovations



1 These commonly include: digital twins; chatbots; the IoT; artificial intelligence and big data; distributed ledger technologies (DLT) such as blockchain; and augmented and virtual reality, among others.

This brief provides an overview of blockchain[1] technology and its applicability in the power sector, with a focus on the means by which it can enable the integration of more renewable energy. With "smart contracts",[2] blockchain has the potential to play a major role in helping to integrate renewables by automating processes, increasing power system flexibility and reducing transaction costs. It can simultaneously accelerate the adoption of other technologies, such as storage and electric vehicles (EVs), leading to improved grid management and system operation.

With the relatively recent increase in power sector complexity comes a need for greater intelligence and transparency. Surging numbers of smart devices coming online are generating vast amounts of granular data – important fuel for burgeoning technologies, such as artificial intelligence, to increase the efficiency of power systems and reduce energy usage. New tools to manage all this data in a secure, efficient and transparent manner are being sought, and blockchain technology is already proving useful. New business models in the energy sector enabled by blockchain technology continue to emerge and evolve, with the spotlight currently on local peer-to-peer (P2P) and wholesale power trading as well as innovative means of project financing in developing countries, among others.

This brief is structured as follows:

I Description

II Contribution to power sector transformation

III Key factors to enable deployment

IV Current status and examples of ongoing initiatives

V Implementation requirements: Checklist

1 *Blockchain is a specific type of distributed ledger technology (DLT), which utilises a chain of blocks as the underlying data structure. There are, however, multiple forms of DLT, such as: blockchains, directed acyclic graphs, hash graphs and distributed hash tables. In general, the term "blockchain" is used as a catchall for DLTs. This principle has also been applied to this document, as both terms are used throughout.*

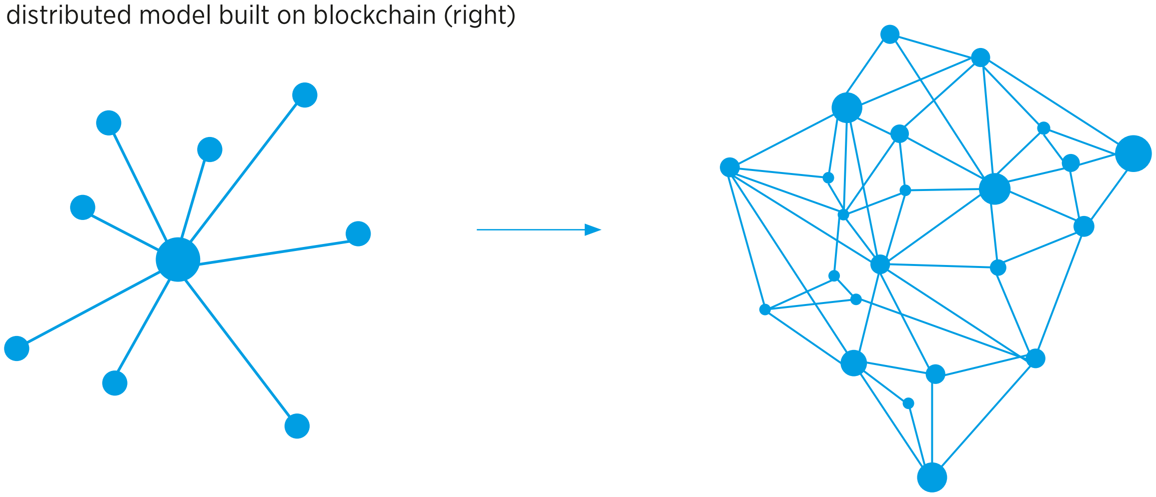
2 *Contracts programmed to self-execute when specified conditions are met.*

I. DESCRIPTION

Distributed ledger technology (DLT), such as blockchain, is a relatively recent technological innovation that has wide-ranging implications for many sectors. While the cryptographic technologies underpinning blockchains have been around for some time, their combination into a useful package was truly innovative. In the power sector, that combination matched with the proliferation of distributed energy resources and grid-interactive devices is what makes blockchain potential exciting. But what *are* blockchains exactly? Blockchains are essentially immutable digital ledgers that can be used to securely record all transactions taking place on a given network – once data is sealed within a block it cannot be changed retroactively. This includes not only financial transaction data, but almost anything of value.

The technology is enabling a new world of decentralised communication and co-ordination, by building the infrastructure to allow peers to safely, cheaply and quickly connect with each other without a centralised intermediary. Cryptography ensures security and data integrity, while privacy remains intact. Combined with an economic incentive framework also known as a consensus mechanism,[3] this allows for the peer-to-peer validation of transactions through enhanced security, better data management and increased ability to co-operate among multiple actors, while bypassing the need for a trusted, centralised intermediary to verify transactions.

Figure 2 Moving from a traditional centralised model with a trusted intermediary (left) to a decentralised, distributed model built on blockchain (right)



3 *A set of rules that decides on the contributions by the various participants of the blockchain. Proof of work is a common consensus algorithm used by blockchains such as Bitcoin and Ethereum, whereby "miners" solve complex cryptographic puzzles before they can publish new blocks to the chain.*

In the power sector, blockchain technology offers many possibilities. It could pave the way for sophisticated networks that decentrally and democratically manage the entire distributed energy value chain in a more disintermediated[4] and efficient way (Figure 2). This includes the management of power generation and distribution, sales, billing, payments, innovative financing mechanisms, contract management, and trading and incentives.

This shift from centralisation to decentralisation gives rise to the potential for every participant in a network to transact directly with every other network participant without a third-party intermediary to validate and secure transactions, thus reducing transaction cost and time, and establishing the backbone for a new type of decentralised internet. Today, most blockchains are permissionless[5] public ledgers based on open protocols, such as Bitcoin and Ethereum, in which anyone can connect to the blockchain and participate. There are, however, a number of permissioned[6] blockchains currently in development, used primarily for enterprise solutions.

Importantly, blockchain technologies are still in their infancy, and therefore questions remain about security, scalability and governance. New projects based on blockchain aim to disintermediate: protection of personal data; electronic voting; cross-border micropayments; supply chain management; and electricity generation and usage, among others. These projects are built upon a wide range of protocols utilising a variety of consensus algorithms. However, blockchain is evolving, and new technologies are proving to be far more energy efficient, faster and more scalable than their predecessors. Many blockchains even allow for the coding of self-executing contracts, or "smart contracts", meaning digital contracts that are programmed to self-execute when specified conditions are met (*e.g.* if A receives X kilowatt hours [kWh], then B automatically receives Y monetary units as payment) – again, without the need for a centralised, trusted authority. This is a concept first pioneered by Nick Szabo in 1994 and employed by the Ethereum blockchain in 2013 (Blockgeeks, 2018).

With the increasing number of internet-connected smart devices, the surface area for cyberattacks is also expanding and growing power sector interconnectedness is exacerbating these security risks. Tools such as blockchain, due to its decentralised and cryptographically[7] secured nature, offer new means of securing networks and increasing transparency, thereby helping to reduce fraud and abuses of privacy which have become increasingly common.

The role of blockchain smart contracts in the power sector

The power sector is among those most discussed as being prone to disruption through blockchain integration. The highly centralised market structure and regulatory environment make power a highly suitable sector for the application of blockchain technology, as electrons can be traded instantaneously with minimal transaction fees in a decentralised network (*e.g.* from neighbour to neighbour), while payments can be processed simultaneously.

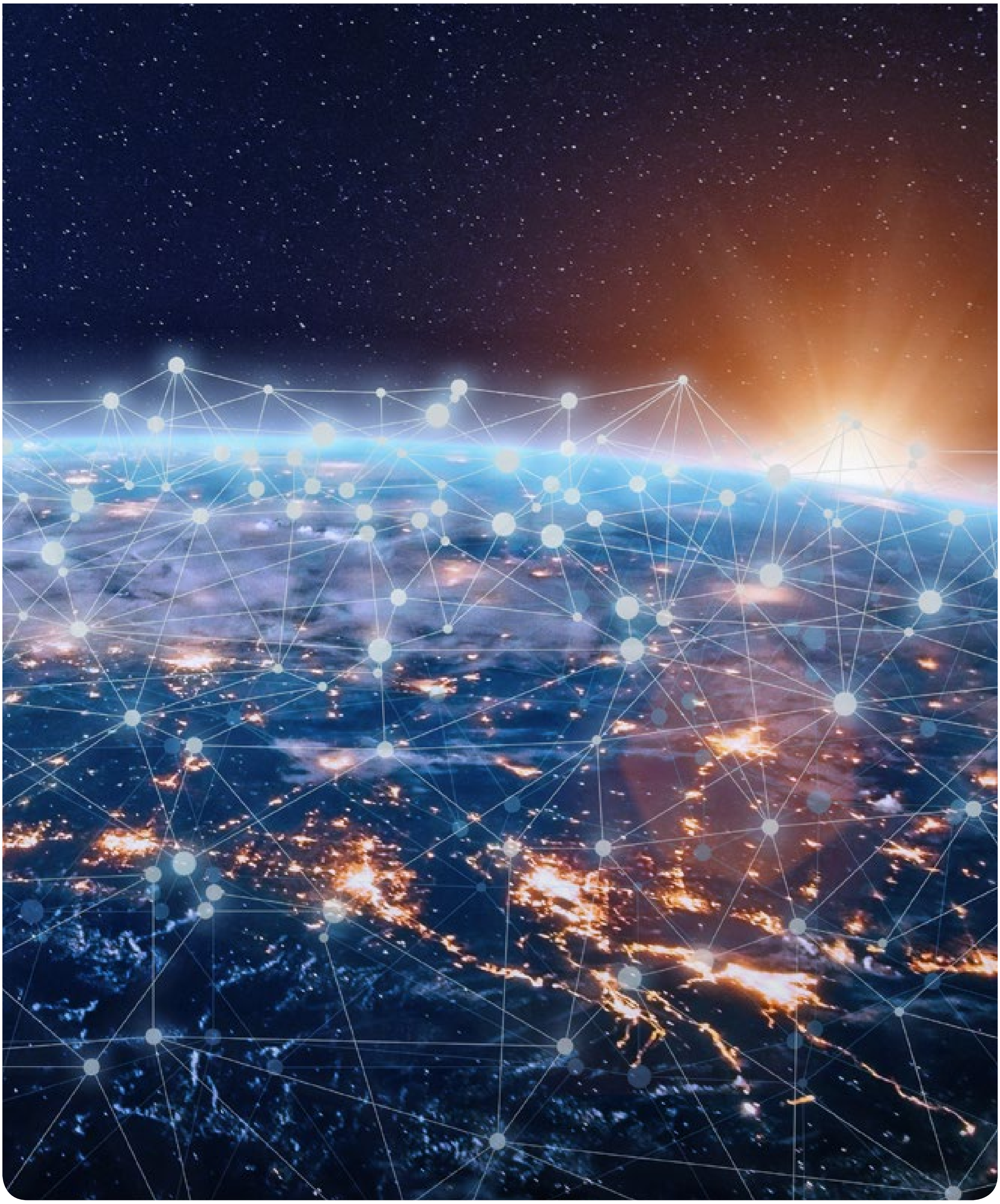
4 Disintermediation is the removal of intermediaries.

5 In a permissionless blockchain, anyone can join the network, participate in the process of block verification to create consensus and also create smart contracts. A good example of permissionless blockchain is the Bitcoin and Ethereum blockchains, where any user can join the network and start mining. These offer greater transparency and decentralisation than permissioned blockchains, but face greater challenges in terms of scalability and speed.

6 A permissioned blockchain restricts the actors who can contribute to the consensus of the system state. In a permissioned blockchain, only a restricted set of users have the rights to validate the block transactions. A permissioned blockchain may also restrict access to approved actors who can create smart contracts. Recent developments have seen permissioned blockchains such as Energy Web Chain emerge, which rely on proof of authority for consensus.

7 Cryptography is the practice of techniques for secure communication. It is a method of storing and transmitting data in a particular form so that only those for whom it is intended can read and process it.

With smart contracts, consumers are transformed into active participants in the market, able to buy and sell their electricity without involving a trusted authority or intermediary. Smart meter solutions can even immediately publish renewable generation data to the blockchain as the power is produced, and carbon reduction incentives, or green certificates, can be determined and earned instantly. Smart contracts enabled by blockchain, and used in concert with smart meter technology, offer a number of efficient, effective and affordable solutions to help transform the power sector, and may ultimately enable truly transactive energy systems (EWF, 2018a).



II. CONTRIBUTION TO POWER SYSTEM TRANSFORMATION

By acting as the foundational data layer on which information, value and electrons are exchanged, blockchain technology has the potential to play an important role in the transformation of the power sector, underpinning the applications that perform the optimisation and co-ordination. Its influence begins with niche uses and spreads with stakeholder awareness and acceptance.

Smart contracts are a key tool enabling the development of the blockchain initiatives presented in Figure 3. By automating the definition of rules and penalties relating to an agreement, while also automatically enforcing obligations, smart contracts have the potential to greatly reduce friction from the establishment and enforcement of contracts by removing the intermediary. This is accomplished while also integrating the security, transparency and immutability features that blockchain technology offers. Smart contracts work on the If-Then premise. An apt metaphor often used to describe these self-executing contracts is that of a vending machine, whereby your purchased item automatically arrives once you deposit payment and make a selection. In the case of smart contracts, the vending machine is the ledger and the products can be anything from kilowatt hours of electricity to real estate deeds.

Smart contracts built on blockchain can help modernise electricity grids by allowing a total system approach to be developed, enhancing the use of renewables, particularly hard-to-integrate intermittent sources, while improving operations and management of network assets. Lower costs, faster processes and greater flexibility are all possible through this shift in the underlying transaction model from centralised to decentralised.

In the not-too-distant future smart contracts might automatically buy and sell power from and to the grid based on real-time price signals, for homes and businesses equipped with the necessary software and smart meters. Furthermore, with hundreds of thousands of new devices connecting to the grid, a way is needed to co-ordinate them effectively and allow them to play their full role in balancing the grid. As the grid moves from a top-down centrally managed system to a bidirectional market with many more assets at the grid edge, co-ordination becomes key. Blockchain is a data management tool that can facilitate effective co-ordination between many actors, with low transaction costs.

Some of the transformative uses of blockchain possible in the power sector are presented below, emphasising the impact on power sector transformation and renewables integration.

Peer-to-peer power trade

With the potential for a decentralised model based on blockchain to reduce transaction costs, smaller electricity producers could sell excess renewable energy to other network participants, thus, in theory, bringing down prices through increasing competition and grid efficiency. Trusted third parties, such as retailers, may play a much smaller role in a distributed P2P model, and smart contracts will automate processes that previously required manual work and multiple parties (HBR, 2017). With smart contracts, trades can be made automatically using price signals and real-time renewable energy production data throughout the network.

Figure 3 Blockchain initiatives in the power sector

Note: Data as of July 2018.
Based on: Livingston et al. (2018), Applying Blockchain Technology to Electric Power Systems.

Companies are now working on intelligent grids, which use digitalisation and smart contracts to automate the monitoring and redistribution of microgrid energy. By acting as the foundational data layer, DLTs such as blockchain can also assist in achieving the localised goals of power systems, such as the optimisation of distributed energy resources in microgrid networks. Companies such as Power Ledger and LO3 Energy, and research initiatives such as The Energy Collective, have been experimenting with local microgrids, allowing neighbours to make virtual electricity trades using the local grid and potentially allowing consumers to own shares in nearby solar farms, selling their share of the power generated on the open market.

The ability to freely sell one's generated power at market rates to a network of peers provides incentives for increased adoption of distributed renewables. These granular transactions are being enabled through blockchain, but barriers to widespread adoption exist, with the lack of a consistent regulatory environment playing a large role. Energy Web Foundation (EWF) – in collaboration with large energy companies and start-ups – is developing an open-source, scalable blockchain platform specifically designed for the energy sector's regulatory, operational and market needs. The objective is to promote energy sector innovation and accelerate the transition to a decentralised, democratised, decarbonised and resilient energy system (EWF, 2018b).

Grid management and system operation

Blockchain technology allows electricity networks to be more easily controlled, as smart contracts would signal to the system when to initiate specific transactions. This would be based on predefined rules created by the platform, designed to ensure that all power and storage flows are controlled automatically to balance supply and demand. For example, whenever more variable renewable energy is generated than needed, smart contracts could be used to ensure that excess electricity is diverted into storage automatically. Conversely, the electricity held in storage could be deployed for use whenever the generated power output is insufficient. In this way, blockchain technology could directly control network flows and flexibility options, avoiding curtailment of solar and wind energy.

In addition, the exchange and transaction of electricity can be optimised over a wider network, which would help bring down costs while increasing the integration of variable renewables. When renewable energy sources in a fixed geography are unreliable, load sharing over a wider area reduces the variability and the need for storage by increasing trade. Smart contracts could also be used to manage balancing activities and virtual power plants, both relevant for a power system with very high shares of variable renewable energy.

Assuming blockchains are able to scale up the number of transactions processed while remaining fast and secure, they could help reduce the complexity of network operation. For example, a distribution system operator (DSO) or transmission service operator (TSO) could operate a (private) permissioned blockchain; all devices connected to the DSO or TSO electricity grid would also be connected to its blockchain, enabling the tracking of transactions. This would support the DSO or TSO in not only supervising, but also intervening if necessary. For example, Elia, Belgium's TSO, is currently learning how to use blockchain technology initially to target certain processes in the area of demand response, in particular registration, measurement and verification, and financial settlement (EWF, 2018c). In addition, Electron is working with an industry consortium, including National Grid, EDF and Shell, to look at how grid-edge assets can be integrated into the grid to reduce costs and carbon emissions while increasing reliability. TenneT, a TSO in Germany, is using blockchain in a pilot project to procure balancing services from behind-the-meter batteries.

Financing renewable energy through hybrid asset classes

Despite a staggering number of people lacking access to energy globally, and hundreds of billions being invested in renewable energy annually by the public and private sectors, the roll-out of renewable energy is not moving quickly enough to address climate needs while improving access to modern energy services. An opening still appears to exist for financing mechanisms and marketplaces to bring together energy demand and finance supply. Blockchain technology offers an attractive platform for this through its potentially low transaction costs, efficient processing and security features provided by smart contracts, and its payment capabilities. Companies such as The Sun Exchange and ImpactPPA aim to accelerate the financing of renewable energy using the power of blockchain.

P2P ledgers have ushered in an era of new "crypto" assets that can be freely traded by the general public or used as tokens to purchase goods and services on a specific network. Since the digital assets change hands at the agreed value directly between the buyer and the seller, commissions are saved in the process. These blockchain-based assets are quite promising for the financing of renewable energy projects. Token crowd sales are being used as a way to raise capital for infrastructure, while the tokens themselves will later change hands just as money, with the difference being that this is money that may yield increased value over time, as shares in a company might. In a sense, tokens represent the gross domestic product (GDP) of a network: the more a network (Ethereum for example) is used, the more valuable the tokens become as their usefulness increases.

Management of renewable energy certificates

In many cases, renewable energy certificates (RECs) are awarded on the basis of estimates and forecasts rather than on actual generation. In the European Union, guarantee of origin (GO) legislation is in place that requires the issuing of GOs to be based on measurement of the electricity produced. These GOs can be traded within the European Union, and can be used to provide proof that the electricity consumed was indeed renewable. This legislation also stipulates that "…with a view to ensuring a unit of electricity from renewable energy sources is disclosed to a customer only once, double counting and double disclosure of guarantees of origin should be avoided…" (European Union, 2009). The potential role for blockchain is clear, as double spending is prevented via cryptography and decentralised consensus.

With blockchain technology, distributed renewable energy producers (*e.g.* rooftop solar) can be awarded RECs in real time, as their power is generated. Sensors and smart contracts can record and propagate real-time generation data throughout the network. A central verification agency to verify generation data may no longer be needed as all data would be secured and viewable on the blockchain. With this new technology, public agencies administering RECs could reduce costs by streamlining data verification and automating REC awarding. Notably, however, that verification of meter readings is still an issue that requires exploration in a decentralised solution (McKinsey & Company, 2018).

Electric mobility

Blockchains might also play an important role in the development of electromobility, underpinning the platform that co-ordinates EV charging. EV owners would be able to stop at any charging station, including residential locations, that is registered on the blockchain and trade power for payment in real time, without any centralised intermediary required. Smart contracts would also allow for automatic and secure P2P payments. By providing the basis for a larger and more efficient charging network, blockchains could enable widespread adoption of not only e-mobility, but also the distributed renewable energy generation needed to power it.

Rural electrification and increased access to modern energy services

While not a main aim of the initiatives discussed above, progress in rural electrification may be achieved due to the burgeoning use of blockchain in the power sector. Nearly 1 billion people still live without reliable access to electricity – 500 million in Africa and more than 400 million in the Asia-Pacific region alone (IEA, IRENA, UN, WBG and WHO, 2018). By allowing local solar generators to sell power to their surrounding neighbours, blockchains can help facilitate the distribution of small amounts of energy in underserved areas when combined with smart and innovative financing schemes, mobile applications and digital sensors.

This approach can work as follows. The prospective generator installs a blockchain-enabled solar panel on credit from the installer, using a mobile phone to pay for the hardware in instalments and incurring minimal fees. Once the solar installation is paid for, the owner can sell excess solar power to nearby consumers as needed. Power requests and payments can be made seamlessly via mobile phone. The lighter fixed infrastructure involved with blockchains and mobile micropayments allows these networks to thrive where other infrastructure – wires, traditional loan structures and centralised energy authorities, for example – might be too cumbersome (McKinsey & Company, 2018).

III. KEY FACTORS TO ENABLE DEPLOYMENT

Maturing technology: Improving performance and scalability

Blockchain networks need to scale up to enable the widespread adoption of the technology in the power sector and in other sectors. This includes: increasing the number of transactions per second (TPS) processed in these networks; reducing block time (how often computations on the blockchain are bundled and verified); and increasing the block size limit (the amount of transactions bundled in each block).

Early protocols, including Bitcoin and Ethereum, boasted throughputs of about 10 TPS and 30 TPS, respectively. VisaNet, the centralised processing service for the international Visa network, can handle more than 65 000 TPS (Visa, 2018). Mass adoption in the power sector and others would require thousands of TPS, particularly as the number of internet-connected devices continues to increase. There exists a trade-off, however: the more decentralised a network is (*i.e.* the larger the number of individual nodes processing transactions), the harder it is to maintain a higher number of TPS. If decentralisation is not an important consideration for a particular use case, blockchain is most likely not the appropriate tool to process transactions. The pros and cons of decentralisation and speed are widely discussed in various fora today.

A promising means of tackling scaling is the use of parallel interoperable chains, or "sidechains". This approach essentially delegates some computational responsibility to subordinate chains, which report and notarise their results to other chains. The network thus achieves consensus by parallel processing computations, rather than burdening a single chain.

Consider a hypothetical example for the German energy market. Rather than a single blockchain for all of Germany, there could be one main chain for Germany, but then also separate chains for each of its 16 federal states, and 20 more chains for each larger city in each of the states. The result would be 337 chains stacked on three layers, increasing throughput by three orders of magnitude compared to a single chain. This architecture would also address data sovereignty regulations, which require data to be stored within specific geographical boundaries (EWF, 2018d).

Another potential way to manage the speed and scale issues associated with an open platform that uses proof of work for consensus is to employ an alternative consensus algorithm, such as proof of stake or proof of authority.[8] In addition, certain data can be stored off blockchain or frozen, thereby allowing enhanced processing times. Importantly, blockchain technology is still developing, and performance and scalability will continue to improve with time. To nurture this development, more developers will be needed. The current shortage of developers required to code the decentralised applications, and the blockchains on which they run, has led to high development costs – a substantial hurdle.

8 Proof of authority (PoA) is a replacement for proof of work, which can be used for private chain setups. It does not depend on nodes solving arbitrarily difficult mathematical problems, but instead uses a set of "authorities" – nodes that are explicitly allowed to create new blocks and secure the blockchain. Hashgraph, a leading example of a network using PoA for consensus, uses a governance model where a council, consisting of 39 public organisations in a variety of fields serving 3-year terms, make decisions for the platform as a whole. These 39 organisations act as network authorities.

Establishing clear and consistent regulations

The regulatory environment for blockchain remains uncertain. A lack of blockchain procedures or global regulation also means that the procedure for handling disputes, wrongdoings and transaction reversals is inconsistent and legally uncertain. Due to the nature of blockchains and the generation of coins or tokens to incentivise the validation of transactions (*i.e.* mining), a new asset class has emerged to reflect the inherent value of these coins. Because of the substantial funds being invested in this growing asset class, blockchain technology as a whole is facing increased scrutiny, and governments are grappling with how to adapt regulation and taxation. Markets with less regulatory uncertainty are seeing a boom in blockchain-related start-ups and overall adoption.

In March 2017, ELECTRIFY, Singapore's first retail electricity marketplace, raised over USD 30 million from investors to build their platform. ELECTRIFY's Marketplace 2.0 system will allow consumers to browse and purchase electricity from a variety of providers starting in the second half of 2018, while smart contracts will connect to digital wallets that facilitate bill payment and platform services fees (Electrify.Asia, 2017). Grid+ in the United States, WePower in Europe and PowerLedger in Australia have raised similar amounts to build their respective platforms.

Due to the overarching uncertainty and the overall lack of awareness surrounding blockchain technology, most blockchain platforms in the power sector are currently being tested only for behind-the-meter applications as part of regulatory sandboxes established in certain countries to test these technologies. This requires minimal changes to the energy regulatory regime and provides consumers with more flexibility or independence. However, blockchain technology has the potential to transform larger interconnected grids for which the stakeholders will initially need established regulations and technical standards for operations. To achieve this, power sector regulatory environments should be clearly defined and stable, so that tools like blockchain can be developed and used for specific applications where value can be added. Frameworks that better enable and encourage decentralised transaction models would more effectively facilitate the use of blockchain technology. Clear and consistent regulations are needed to nurture this new decentralised internet. Policy makers and regulators need a clear understanding of blockchain use cases and capabilities before being able to properly address policy and regulatory needs.

Blockchain technology might hold the potential to simplify the process of regulation and increase efficiency through the use of data analytics. If regulators gain access to primary records and real-time information of all involved participants, they could then analyse and understand all the processes in which the participating entities are involved. Furthermore, blockchain could simplify the interaction between regulators and regulated entities. For example, increased transparency regarding DSO activities, via the blockchain, could change the way network operators manage their grids.

When it comes to standards, an important question remains: How can we ensure compatibility between different blockchain technologies, so that they can scale up and have an impact? Interoperability between different blockchain solutions remains an issue.

Reducing power consumption

Proof-of-work technologies, such as Bitcoin and Ethereum, rely on mining[9] to validate transactions and secure the network by solving complex cryptographic puzzles. In early 2018, each Bitcoin transaction required a vast amount of computing power, and thus electricity. Each transaction required approximately 300 kWh, meaning the Bitcoin network as a whole required a continuous 3.4 gigawatts (GW) or 30 terawatt hours (TWh) per year, more than the entire country of Austria (Krause and Tolaymat, 2018; Digiconomist, 2018a).

9 Mining means securing the blockchain by validating transactions and adding new blocks to the chain through the solving of complex mathematic puzzles, which is very power intensive. As more computing power is added to the network, the average number of calculations required to create a new block increases, thus increasing validation difficulty.

For blockchain technology to sustainably transform the power sector, along with countless others, a shift from proof of work to other means of transaction validation and network consensus achievement, such as proof of stake,[10] proof of authority, or web 3.0 technologies such as non-linear "tangles",[11] will be required. Ethereum is currently in the process of shifting to a proof-of-stake validation model to dramatically increase transactions per second while drastically reducing power requirements; it is seeking to complete this transition by 2019 or 2020. Notably, many power sector applications of blockchain currently use less energy-intensive protocols that do not rely on proof of work.

Enhancing grid infrastructure

Blockchain technology is extremely versatile and is replicable in any geography with a grid of substantial size. To optimise the use blockchain technology for renewable energy, it is crucial to move towards a more interconnected, technology-enabled smart grid. Currently, many companies are forced to make their own smart meters because they cannot access the data of legacy companies. Grid-interactive infrastructure is needed to take advantage of the benefits that DLTs such as blockchain provide. However, it may take some time and sustained effort to install smart digital meters and other devices to facilitate interconnectivity and increase the amount of transactions processed via blockchain technologies. Additionally, with respect to building out infrastructure, people are still needed to maintain poles and wires and to build new physical grids in remote locations.

Better understanding of the technology applications and developing user-friendly solutions

As blockchain technology matures, it becomes more versatile and the number of uses grows. Despite the numerous potential benefits of blockchain solutions in the power sector for retail users (frictionless P2P trade and payments, instant collection of RECs, among others), new applications with user-friendly interfaces are needed. To provide a straightforward, consistent and positive experience, applications need to be developed for use by individual consumers and small-scale renewable energy generators. For that, a better understanding of this technology and its applicability in all dimensions of the power sector is needed. Current electricity trading platforms are geared towards large-scale brokers and are not intuitive or accessible to the general public.

The ability to easily purchase a small share of a nearby solar farm on your mobile phone and collect revenues based on the power generated, or use it for your own residential consumption (all tracked in real time on your mobile device), will open up access to renewable electricity to a swathe of new consumers. A more transparent and user-friendly solution will also help catalyse small-scale investments in blockchain technologies worldwide, spurring even more innovation in this new field (EWF, 2018d).

10 Unlike the proof-of-work system, in which the user validates transactions and creates new blocks by performing a certain amount of computational work, a proof-of-stake system requires the user to show ownership of a certain number of cryptocurrency units. The creator of a new block is chosen in a pseudo-random way, depending on the amount of coins a user holds.

11 Also known as directed acyclic graph (DAG) technologies. A directed graph data structure uses a topological ordering. The sequence can only go from earlier to later. DAG is often applied to problems related to data processing, scheduling, finding the best route in navigation, and data compression.

IV. CURRENT STATUS AND EXAMPLES OF LEADING INITIATIVES

Recently, Blockchain2business and SolarPlaza analysed over 150 leading companies and pilot projects working with blockchain and energy. The following are some of the key insights (B2B, 2018):

- **Over 46%** of these blockchain energy start-ups are concentrated **in Europe**.
- The **top 3** countries are the **United States, Germany** and the **Netherlands**.
- The most common use is **P2P energy trading**.
- Around **50%** of the projects use the **Ethereum** blockchain.
- Close to **74%** of the companies were started/ founded between **2016** and **2018**, which reflects the early stage of the technology.

Power consumption:

- In early 2018, each **Bitcoin transaction** required approximately **300 kWh**, enough to power over 8 US households for a full day. The Bitcoin network as a whole required a continuous **3.4 GW** or **30 TWh** per year, more than **Austria's** annual electricity consumption (Krause and Tolaymat, 2018; Digiconomist, 2018a; Digiconomist, 2018b).
- **The two largest blockchain**s (Bitcoin and Ethereum) combined consume **42.67 TWh** annually, **0.19%** of the **world's electricity** (Digiconomist, 2018a; Digiconomist, 2018b).
- New means of reaching consensus, such as **proof of stake** and **proof of authority**, will help to greatly reduce power consumption as they are adopted.

A separate study by GTM Research/Wood Mackenzie Power and Renewables assessed the scale of current blockchain activity in the power sector (Table 1).

Currently, start-ups and consortiums focused on the power sector are largely choosing to build their second-layer applications on the Ethereum platform, due to its size (large number of nodes which work to validate transactions), ability to host smart contracts, stability, and plans for increased scalability and speed with a shift in the consensus model to proof of stake. A variety of uses for blockchain are being studied in the power sector at the moment, but the main areas of focus revolve around the optimisation of grid management processes and P2P, peer-to-business (P2B) and business-to-business (B2B) wholesale electricity trading without intermediation.

On 10 April 2018, 22 European countries[12] signed a declaration on the establishment of a European Blockchain Partnership. It is designed to act as a vehicle for co-operation among EU member states to exchange experience and expertise in preparation for the launch of EU-wide blockchain applications across the Digital Single Market. The aim is to ensure that Europe continues to play a leading role in the development and roll-out of blockchain technologies, including for use in the power sector (European Commission, 2018).

12 *Since the initial signing of the declaration on 10 April 2018, 5 more EU member states have joined the partnership, bringing the total number of signatories to 27.*

Table 1 Extent of blockchain activity in the power sector

Description	Value
Number of companies working in blockchain in the power sector	189
Number of companies leading blockchain projects in Grid Edge space	32
Amount invested in blockchain power companies	USD 466 million, 79% of which came from Initial Coin Offerings
Amount raised by start-up companies in 2017 to apply blockchain technology to power sector	USD 300 million
Number of projects happening globally	71 announced

Note: Data valid as of 31 July 2018.
Source: Metelitsa (2018), "A snapshot into blockchain deployments and investments in the power sector".

In early March 2018 the International Energy Research Centre and others launched EnerPort, a new project which aims to accelerate P2P electricity trading in Ireland through blockchain. Some of the challenges to be addressed include: trust and validation of transactions made in distributed energy networks; how to foster stronger consumer engagement within that market; and how to free up the trading regulations within local networks as technologies such as electricity storage systems, EVs and smart home devices are deployed (IERC, 2018).

The launch of the Open Electricity Market in Singapore has empowered consumers with more choices. They can now choose green price plans offered through a variety of retailers who, today, can offer green price plans by bundling physical electricity with tradable certificates of green energy attributes, also known as RECs. With SP Group's recently launched blockchain-powered REC Marketplace, retailers and consumers are now able to purchase RECs in a more simple, secure and cost-effective manner, to better meet increasing customer demands for green energy sources.

The following tables present a non-exhaustive sample of companies, consortiums, foundations and groups working at the intersection of blockchain and energy, particularly renewable power. When blockchain technology and the world of energy intersect, several application categories emerge. Among these categories are: P2P transactions, grid management and system operation, financing renewable energy development, management of RECs and certification of origin, and electric mobility. For each of these categories, a series of companies, consortiums, foundations and working groups will be mentioned, indicating its name, country of origin, as well as a brief description of it.

Table 2 Example of initiatives that use blockchain for peer-to-peer electricity trading

Actor	Business	Country	Brief description
National Renewable Energy Laboratory	Government-level regulatory initiatives	United States	NREL is partnering with Blockcypher to demonstrate transactions of distributed energy resources across multiple blockchains.
Conjoule	Private company	Germany	Conjoule offers a blockchain platform designed to support P2P trading of energy among rooftop photovoltaic (PV) owners and interested public-sector or corporate buyers.
Electrify.Asia	Private company	Singapore	Electrify.Asia is developing a marketplace which acts as a web and mobile platform allowing consumers to purchase energy from electricity retailers or directly from their peers (P2P) with smart contracts and blockchain.
Electron	Private company	United Kingdom	Electron began with a blockchain-based solution to help customers in the United Kingdom switch energy suppliers, but has since been communicating a vision of leveraging its platform to support broader energy trading and grid-balancing solutions.
Greeneum	Private company	Israel	Greeneum is running test nets and pilots for its P2P energy trading platform in Europe, Cyprus, Israel, Africa and the United States. It expects to have a viable product platform out by mid-2018.
LO3 Energy	Private company	United States	Backed by Siemens, P2P blockchain developer LO3 Energy operates the Brooklyn Microgrid, which augments the traditional energy grid, letting participants tap into community resources to generate, store, buy and sell energy at the local level. This model makes clean, renewable energy more accessible, and keeps the community resilient to outages in emergencies, among many other economic and environmental benefits.
Power Ledger	Private company	Australia	The Power Ledger platform forms P2P energy transactions by recording both the generation and consumption of all platform participants in real time. The company is rolling out pilot projects for its blockchain platform, built to support a broad range of energy market applications, in Australia and New Zealand.
Sonnen	Private company	Germany	Redispatch measures prevent regional overloads on the grid. In this pilot project with sonnen eServices, a network of residential solar batteries will be made available to help address the limitations associated with wind energy transmission capacity. Blockchain technology provides the operator from TenneT with a view of the available pool of flexibility, ready to activate at the push of a button, after which the blockchain records batteries' contribution.
Axpo	Utility	Switzerland	Axpo launched a P2P platform that allows consumers to buy electricity directly from renewable producers.
National Grid UK	Utility	United Kingdom	National Grid is backing the energy trading platform launched by Electron.
Vattenfall	Utility	Sweden	Vattenfall is piloting Powerpeers, a marketplace for P2P energy trading; it has joined the Enerchain framework.

Table data sourced from: GTM (2018), "15 firms leading the way on energy blockchain", www.greentechmedia.com/articles/read/leading-energy-blockchain-firms; SolarPlaza (2018), Comprehensive Guide to Companies involved in Blockchain & Energy; Livingston et al. (2018), Applying Blockchain Technology to Electric Power Systems; as well as individual websites.

Table 3 Examples of initiatives that use blockchain for grid management and system operation

Actor	Business	Country	Brief description
German Ministry of Economic Affairs and Energy	Government-level regulatory initiatives	Germany	Piloting a large-scale decentralised and integrated platform for renewable generation, transmission and distribution infrastructure.
Energy Web Foundation	Non-profit organisation	Switzerland	Established in February 2017 by Grid Singularity and the Rocky Mountain Institute, Energy Web Foundation (EWF) is a global non-profit organisation focused on accelerating blockchain technology across the energy sector and is developing a new open-source, energy-focused blockchain platform that provides the functionalities needed to implement energy sector use cases at scale.
Ponton	Private company	Germany	Operates Enerchain, a blockchain-powered wholesale electricity trading platform.
Sunchain	Private company	France	Distributed solar power storage for private prosumers.
Eneco	Utility	Netherlands	Piloting a blockchain application to create a decentralised heating network in Rotterdam.
Enel	Utility	Italy	Joined Enerchain framework to conduct P2P trading in the wholesale energy market.
E.ON	Utility	Germany	Joined Enerchain framework to conduct direct electricity trading between energy companies.
Iberdrola	Utility	Spain	Joined Enerchain framework to conduct direct electricity trading between energy companies.

Table data sourced from: GTM (2018), "15 firms leading the way on energy blockchain", www.greentechmedia.com/articles/read/leading-energy-blockchain-firms; SolarPlaza (2018), Comprehensive Guide sto Companies involved in Blockchain & Energy; Livingston et al. (2018), Applying Blockchain Technology to Electric Power Systems; as well as individual websites.

Table 4 Examples of initiatives that use blockchain for management of renewable certificates and certification of origin

Actor	Business	Country	Brief description
Sustainable Energy Development Authority	Government-level regulatory initiatives	Malaysia	Invested in P2P a marketplace project run by Power Ledger.
Reneum Institute	Non-profit	Singapore	Records electricity generation data gathered directly from smart meters of renewable energy projects to help digitize, standardize and democratize the market for renewable energy credits and scale up investments into new generation assets worldwide.
CarbonX	Private company	Canada	P2P carbon credit trading platform.
ElectriCChain	Private company	Andorra	Market platform for auditing decentralised solar power generation data.
Energy Blockchain Labs	Private company	China	Platform for trading decentralised carbon assets.
SolarCoin	Private company	United States	SolarCoin was launched in 2014 as a rewards programme for solar electricity generation, with one of its coins equalling a megawatt hour of production. The scheme is set to reward 97 500 TWh of generation over 40 years, but for now its value remains low.
Veridium	Private company	United States	Veridium is a financial technology firm aiming to create a new asset class called "EcoSmart Commodities". Veridium will provide a new vehicle for corporations to embed environmental replacements into the cost of their products.
Engie	Private company	France	Working with Air Products to certify renewable energy use in production processes.
Volt Markets	Private company	United States	Platform that issues, tracks and trades RECs.
Russian Carbon Fund	Utility	Russian Federation	Developing an audit system for climate projects with E&Y.
SP Group	Utility	Singapore	Launched blockchain-enabled platform to transact RECs.

Table data sourced from: GTM (2018), "15 firms leading the way on energy blockchain", www.greentechmedia.com/articles/read/leading-energy-blockchain-firms; SolarPlaza (2018), Comprehensive Guide to Companies involved in Blockchain & Energy; Livingston et al. (2018), Applying Blockchain Technology to Electric Power Systems; as well as individual websites.

Table 5 Examples of initiatives that use blockchain for financing renewable energy deployment

Actor	Business	Country	Brief description
Ministry of Micro, Small and Medium Enterprises	Government-level regulatory initiatives	India	Using Ethereum blockchain to manage supply chain logistics for renewable energy-powered textile looms.
ImpactPPA	Private company	United States	While most energy-based blockchain players offer a token for trading, California-based ImpactPPA has two: one to fund projects and one to consume energy. The company is targeting the estimated 16% of the world population that lacks a reliable source of energy.
M-PayG	Private company	Denmark	Pay-as-you-go solar energy for households across the developing world.
MyBit	Private company	Switzerland	MyBit is designed to help crowdfund solar panels by distributing the ownership of each system across several owners. The company raised the equivalent of around USD 2.7 million in a token sale in August.
The Sun Exchange	Private company	South Africa	The Sun Exchange aims to let supporters around the world crowdfund PV down to the level of an individual solar cell and lease them to schools and businesses in Africa. The company's marketplace is focused on funding and building new generation systems, rather than trading power. Sun Exchange has been operational for several years and has successfully funded four solar projects.
WePower	Private company	Lithuania	WePower is developing an Ethereum-based platform to fund renewable energy projects through the sale and trading of the "tokenised" energy produced by those systems. The company raised USD 40 million in funding in 2017.
Direct Energy	Utility	United States	Partnered with LO3 Energy to offer "micro-energy hedging" in energy markets.
Endesa	Utility	Spain	Joined Enerchain framework to conduct direct electricity trading between energy companies.
Enercity	Utility	Germany	Accepts bitcoin for bill payments.

Table data sourced from: GTM (2018), "15 firms leading the way on energy blockchain", www.greentechmedia.com/articles/read/leading-energy-blockchain-firms; SolarPlaza (2018), Comprehensive Guide to Companies involved in Blockchain & Energy; Livingston et al. (2018), Applying Blockchain Technology to Electric Power Systems; as well as individual websites.

Table 6 Examples of initatives that use blockchain for electric mobility

Actor	Business	Country	Brief description
eMotor Werks	Private company	United States	P2P EV charging network through partnership with Share&Charge platform.
MotionWerk	Private company	Germany	Partnership with Slock.it on Share&Charge platform, which provides decentralised EV charging locations.
Slock.it	Private company	Germany	Partnership with MotionWerk to develop Share&Charge platform.
Chubu Electric Power Company	Utility	Japan	Piloting blockchain-based EV charging service.
Enexis	Utility	Netherlands	Prototyping IOTA-enabled cryptocurrency transactions for EV charging.
Pacific Gas and Electricity (PG&E)	Utility	United States	Has approved eMotor Werks and Oxygen Initiative as vendors for its 7 500 EV charging station expansion plan.
TenneT	Utility	Germany	Developing blockchain-based system that integrates household batteries and charging for EVs.

Table data sourced from: GTM (2018), "15 firms leading the way on energy blockchain", www.greentechmedia.com/articles/read/leading-energy-blockchain-firms; SolarPlaza (2018), Comprehensive Guide to Companies involved in Blockchain & Energy; Livingston et al. (2018), Applying Blockchain Technology to Electric Power Systems; as well as individual websites.

V. IMPLEMENTATION REQUIREMENTS: CHECKLIST

TECHNICAL REQUIREMENTS	**Hardware:** • Smart grid, smart metering • Smart phones or computers
	Software: • Blockchain support software • Smart contracts and cloud platforms
	Communication protocols: • Scale protocols to handle increased transaction loads while maintaining security and increasing speeds • Common interoperable standards along with data storage and identity, smart contracts
POLICIES NEEDED	**Communication protocols:** • Regulation and supervisory role for promoting safe, efficient and cost-effective electricity transmission and exchange • Regulation for the interaction of new blockchain-based trading and evolution of existing electricity trading regulations • Promotion of decentralised generation
REGULATORY REQUIREMENTS	**Retail market:** • Market regulations that enable electricity exchange between consumers and prosumers (for P2P trading applications), and between prosumers and system operators (for grid transactions) • Customer and producer support and empowerment • Understanding of the need for open market dynamics • Certainty in the ability of prosumers to freely sell power generated from residential distributed energy resources to other grid-connected consumers
	Distribution: • Incentivise DSOs to modify their business models and take up the role of a facilitator and supervisor • Organise payment rules for use of the DSO electricity grid and potentially also the use of the TSO grid if exchange over multiple DSOs is needed
STAKEHOLDER ROLES AND RESPONSIBILITIES	**Distribution:** • Existing roles in the power sector might shift substantially: retailers may face reduced need if all data (and electricity) is exchanged directly between the electricity producer and the consumer, for example • Organise rules to balance consumption and production, and determine consequences if balance is not achieved • Empower consumers through P2P trading and transparent, decentralised information sharing

ACRONYMS AND ABBREVIATIONS

B2B	business-to-business
DAG	directed acyclic graph
DLT	distributed ledger technology
DSO	distribution system operator
GO	guarantee of origin
EV	electric vehicle
P2B	peer-to-business
P2P	peer-to-peer
PoA	proof of authority
PoS	proof of stake
PoW	proof of work
PV	photovoltaic
REC	renewable energy certificate
TSO	transmission system operator

UNITS OF MEASUREMENT

GW	gigawatt
kWh	kilowatt hour
TPS	transactions per second
TWh	terawatt hour

BIBLIOGRAPHY

B2B (2018), *Blockchain & Energy Company Guide*, Blockchain2Business, www.blockchain2business.eu/request-blockchain-company-guide/.

Blockgeeks (2018), "Smart contracts: The blockchain technology that will replace lawyers", Blockgeeks, https://blockgeeks.com/guides/smart-contracts/.

Digiconomist (2018a), *Bitcoin Energy Consumption Index*, Digiconomist, https://digiconomist.net/bitcoin-energy-consumption.

Digiconomist (2018b), *Ethereum Energy Consumption Index* (beta), Digiconomist, https://digiconomist.net/ethereum-energy-consumption.

Electrify.Asia (2017), "Singapore startup raises $30m to let you buy electricity on blockchain", Electrify.Asia, https://electrify.asia/news/singapore-startup-raises-30m-to-let-you-buy-electricity-on-blockchain/.

Engie (2017), "Are blockchains a better way of managing electricity", *Harvard Business Review*, www.engie.com/en/news/blockchain-energy/.

EWF (2018a), *D3A: Decentralized Autonomous Area Agent*, Energy Web Foundation, https://energyweb.org/d3a/.

EWF (2018b), "The Energy Web Chain: Accelerating the energy transition with an open-source, decentralized blockchain platform", Energy Web Foundation. http://www.energyweb.org/papers/the-energy-web-chain.

EWF (2018c), "Belgium's transmission system operator eyes blockchain for demand response", Energy Web Foundation, https://energyweb.org/2018/02/28/belgiums-transmission-system-operator-eyes-blockchain-for-demand-response/.

EWF (2018d), "When it comes to throughput, transactions per second is the wrong blockchain metric", Energy Web Foundation, https://energyweb.org/2018/05/10/when-it-comes-to-throughput-transactions-per-second-is-the-wrong-blockchain-metric/.

European Commission (2018), “European countries join Blockchain Partnership”, European Commission, https://ec.europa.eu/digital-single-market/en/news/european-countries-join-blockchain-partnership

European Union (2009), Directive 2009/28/EC of the European Parliament and of the Council of 23 April 2009 on the promotion of the use of energy from renewable sources and amending and subsequently repealing Directives 2001/77/EC and 2003/30/EC, Official Journal of the European Union, https://eur-lex.europa.eu/LexUriServ/LexUriServ.do?uri=OJ:L:2009:140:0016:0062:en:PDF.

GTM (2018), “15 firms leading the way on energy blockchain”, Greentech Media, www.greentechmedia.com/articles/read/leading-energy-blockchain-firms.

HBR (2017), “How utilities are using blockchain to modernize the grid”, *Harvard Business Review*, https://hbr.org/2017/03/how-utilities-are-using-blockchain-to-modernize-the-grid.

IEA (International Energy Agency), IRENA (International Renewable Energy Agency), UN (United Nations), WBG (World Bank Group) and WHO (World Health Organization) (2018), *Tracking SDG7: The Energy Progress Report 2018*, World Bank, Washington, DC, https://trackingsdg7.esmap.org/data/files/download-documents/chapter_2_electrification.pdf.

IERC (2018), “IERC launches ‘Enerport’ blockchain energy trading project”, International Energy Research Centre, www.ierc.ie/news/ierc-launches-enerport-blockchain-energy-trading-project/.

IRENA (2019), *Innovation landscape for a renewable-powered future*, International Renewable Energy Agency, Abu Dhabi, http://www.irena.org/publications/2019/Feb/Innovation-landscape-for-a-renewable-powered-future.

Krause, M. and T. Tolaymat (2018), “Quantification of energy and carbon costs for mining cryptocurrencies”, *Nature Sustainability*, Vol. 1.

Livingston, D. *et al.* (2018), *Applying Blockchain Technology to Electric Power Systems*, Council on Foreign Relations.

McKinsey & Company (2018), “What every utility CEO should know about blockchain”, McKinsey & Company, www.mckinsey.com/industries/electric-power-and-natural-gas/our-insights/what-every-utility-ceo-should-know-about-blockchain?cid=other-eml-alt-mip-mck-oth-1804&hlkid=8b420a64d444915ac5fb7f8cd4fd9c6&hctky=9976761&hdpid=1ee2d406-c940-469b-a2d4-7df99f6ae7b5#0.

Metelitsa, Colleen (2018), “A snapshot into blockchain deployments and investments in the power sector” (Powerpoint presentation), Wood Mackenzie Power & Renewables.

PowerCompare (2018), “Bitcoin mining now consuming more electricity than 159 countries including Ireland and most countries in Africa”, PowerCompare, https://powercompare.co.uk/bitcoin/.

PV Tech (2018), “SolarCoin: Incentivising solar PV energy production through blockchain innovation”, PV Tech, www.pv-tech.org/guest-blog/SolarCoin-incentivising-solar-pv-energy-production-through-blockchain-innov/.

PwC (2017), “Blockchain – an opportunity for energy producers and consumers?”, PwC, www.pwc.com/gx/en/industries/assets/blockchain-technology-in-energy.pdf.

SolarPlaza (2018), *Comprehensive Guide to Companies involved in Blockchain & Energy*.

UNFCCC (2018), “UN supports blockchain technology for climate action”, United Nations Framework Convention on Climate Change, https://unfccc.int/news/un-supports-blockchain-technology-for-climate-action.

Visa (2018), VISA Fact Sheet, https://usa.visa.com/dam/VCOM/download/corporate/media/visanet-technology/aboutvisafactsheet.pdf.

IRENA
International Renewable Energy Agency

BLOCKCHAIN
INNOVATION LANDSCAPE BRIEF

IRENA HEADQUARTERS
P.O. Box 236, Abu Dhabi
United Arab Emirates

www.irena.org